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Final Report

Experimental Pedestrian Accident Reconstructions—Head Impacts

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16. Abstract

The National Highway Traffic Safety Administration is conducting research to develop methods of reducing pedestrian head injury due to automobile hood contact at speeds less than or equal to 30 miles per hour (48 kph). The development of techniques used to simulate head impacts on vehicle surfaces is described in this paper. The body of work done to develop the test methodology and procedures to simulate head impacts centered on two main tasks. The first task analyzed a set of pedestrian cadaver tests, primarily to develop methods for determining effective head mass and for measuring vehicle deformation, to be used in accident reconstruction testing. The second task completed an extensive set of accident reconstructions and related laboratory impactor response to real-world injury. The results of the best adult accident reconstructions were used to establish correlation between test responses and injury severity experienced in the accidents. Using impactor response as input, two head injury prediction techniques (Head Injury Criterion, HIC, and Translational Mean Strain Criterion, TMSC), were found to correlate well with actual injury severity (expressed either as probability of death based on the three most severe head injuries of each victim, or as overall head injury based on the single highest severity head injury).

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Department of Transportation
National Highway Traffic Safety Administration

TECHNICAL SUMMARY

Report Title Experimental Pedestrian Accident Reconstructions -- Head Impacts	June 1988

Report Author(s)
Timothy A. Hoyt, Thomas F. MacLaughlin and John W. Kessler

The National Highway Traffic Safety Administration is conducting research to develop methods of reducing pedestrian head injury due to automobile hood contact at speeds less than or equal to 30 miles per hour (48 kph). This paper describes the development of techniques used to simulate head impacts on vehicle surfaces. The body of work done to develop the test methodology and procedures to simulate head impacts centered on two main tasks. One task was to analyze a set of pedestrian cadaver tests, primarily to develop test methods for accident reconstructions. The second task was to complete an extensive set of accident reconstructions for the purpose of relating laboratory impactor response to real-world injury.

Accelerometer data, high speed films, and damaged vehicle hoods from eight pedestrian cadaver tests were available for analysis. With this information it was possible to determine the effective head mass of each cadaver upon impact. The head impact velocity could be determined by digitizing the head trajectory in the films. Previous research results had established that similar energy impacts to the hood produce similar dents. The approach used to determine effective head mass was to reconstruct a cadaver head impact using the digitized impact velocity and varying the mass until a test reproduced the cadaver hood deformation. Cadaver test accelerations agreed fairly well with the accelerations from the best reconstructions. In addition to establishing a method for determining effective head mass with a known velocity, a method for defining hood deformation was also established. Both of these methods were used in the accident reconstruction testing which followed.

Thirty-five pedestrian accident cases involving head injury were used in an attempt to correlate the dynamic response of an impactor with actual head injury level. Reproduction of the vehicle damage, dent, using an impactor at the head impact velocity and having the right effective mass was necessary if impactor response was to correlate with injury severity. Approximations of the head impact velocities were obtained by computer simulations using the accident investigation data (vehicle impact speeds) and laboratory data (vehicle stiffnesses) as input. Impactor mass was varied within a narrow range of impact speeds to reproduce the accident vehicle damage. The results of the best adult accident reconstructions were used to establish correlation between test responses and injury severity experienced in the accidents. Using impactor response as input, two head injury prediction techniques (Head Injury Criterion, HIC, and Translational Mean Strain Criterion, TMSC) were found to correlate well with actual injury severity (expressed either as probability of death based on the three most severe head injuries of each victim, or as overall head injury based on the single highest severity head injury).

1.0 INTRODUCTION

A major objective of the Pedestrian Protection Program is to develop and demonstrate vehicle modifications which will result in reduced pedestrian injury severity. A problem determination study (3,9) to determine the relative importance of different pedestrian injuries concluded that three of the most important vehicle source/body area impact combinations are vehicle face/thorax, hood and fender/head, and vehicle face/head. (The vehicle face consists of grille, hood edge, headlight areas, and leading edges of fenders. The hood and fender designation refers to the top surfaces of the hood and fenders.) Consequently, the major focus in the Pedestrian Program is on these three impact combinations.

Before vehicle modifications are developed in the Pedestrian Protection Program for reducing injury severity from these impacts, current production vehicles will be tested to determine baseline performance, identify desirable design features, and provide guidance for improved designs. This requires testing methodologies for assessing the effects of different designs on pedestrian injury severity.

This report focuses on head impact test methods. The objective of this research was to develop 1) the test methodology and procedures that will be used to conduct head impact tests on vehicle faces, hoods, and fenders; and 2) the head injury criterion that will be used to translate laboratory impact responses to injury severity levels.

2.0 BACKGROUND

Research has been previously conducted attempting to develop an impact device and injury criterion to be used for experimentally simulating pedestrian head impacts (1). An impactor consisting of a pneumatic accelerator and a 9.81 pound instrumented headform were constructed. Adult accident reconstructions done in SRL-10 (2) and SRL-39 (3) using this impactor resulted in reasonable correlation between injury severity (AIS) from the accidents and HIC calculated from test results, as shown in Figure 1. However, little or no correlation was seen from child accident reconstructions (Figure 2), where head masses were considerably less than 9.81 pounds. It was concluded that accurate head impact reconstruction was possible only if both the head mass and impact velocity were closely simulated, and that a lower head mass was needed to successfully reconstruct the child cases. This led to the development of a variable mass headform (4) which could be used for both adult and child cases.

3.0 ANALYSIS AND TESTING METHODOLOGY

The body of work done to develop the test methodology and procedures centered on two main tasks. One task was to analyze a set of pedestrian cadaver tests, to develop methods for determining the effective head mass at impact and for measuring the hood dent resulting from the head impact. The second task was to complete an extensive set of accident reconstructions for the purpose of relating laboratory impactor response to real-world injury. These two tasks will be covered in detail in the following sections.

3.1 Cadaver Test Analysis

Eight cadaver tests, conducted by Battelle/Calspan, were available for analysis. The focus of the Battelle study was on pedestrian lower limb injury and did not include cadaver preparations and test procedures required to monitor head injury. Thus, no head injury information is available from this set of tests. Other information from the cadaver tests, however, was very useful. A nine-accelerometer array was mounted in the mouth, and film coverage was provided. Additionally, test vehicle hoods impacted by these cadavers were saved for the purpose of measuring dents. This information enabled us to establish test procedures for simulating pedestrian head impacts. Head injury information was obtained from real world accident cases and is described in Section 3.2, Accident Reconstructions.

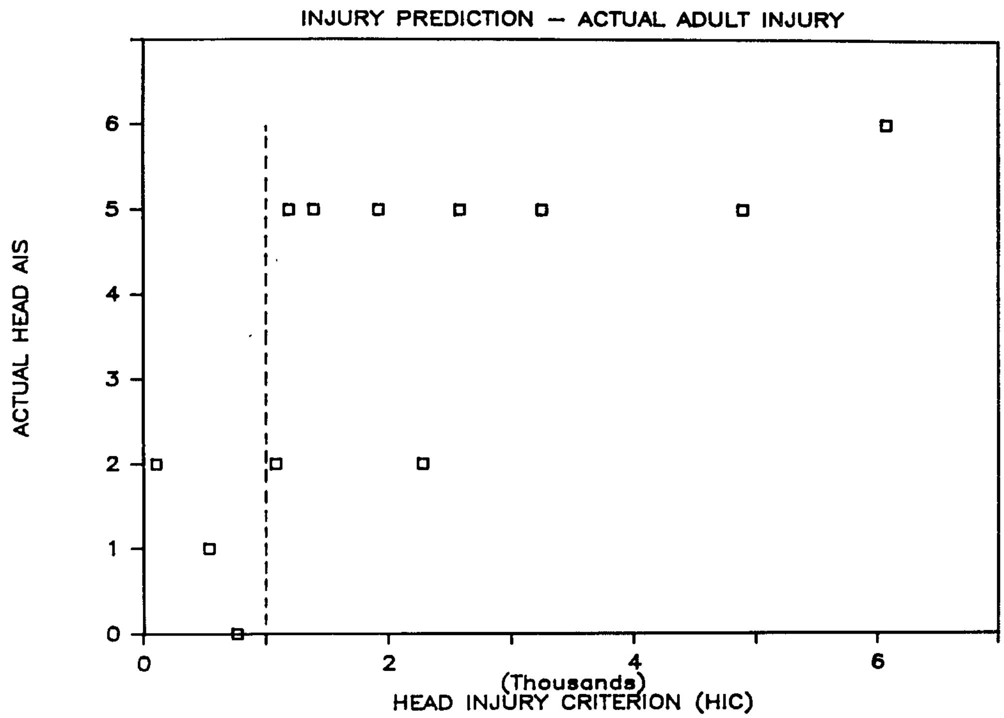

FIGURE 1 -- Correlation to Injury on the Basis of HIC for Previous SRL-10 and SRL-39 Reconstructions of Adult Pedestrian Accidents

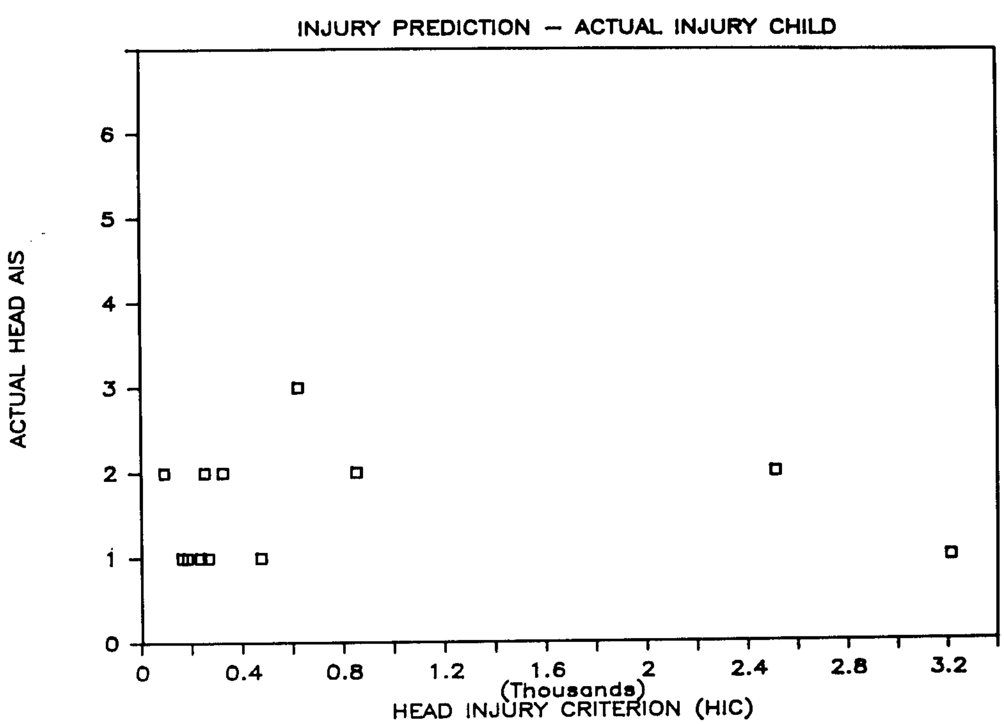

FIGURE 2 -- Comparison of HIC to Actual Injury for Previous SRL-10 and SRL-39 Reconstructions of Child Pedestrian Accidents

In previous testing, a relationship was observed between the energy of an impact and the resulting permanent deformation of the hood. This relationship, shown in Figure 3, was found to be approximately linear over the limited range of impact energies employed, for a single position on a single vehicle. It seemed intuitive that the constants in the linear relationship would be dependent upon the stiffness characteristics of the impact location, but the degree of sensitivity was unknown. It appeared that this relationship could be used for determining effective head mass, if impact velocity and permanent deformation were known.

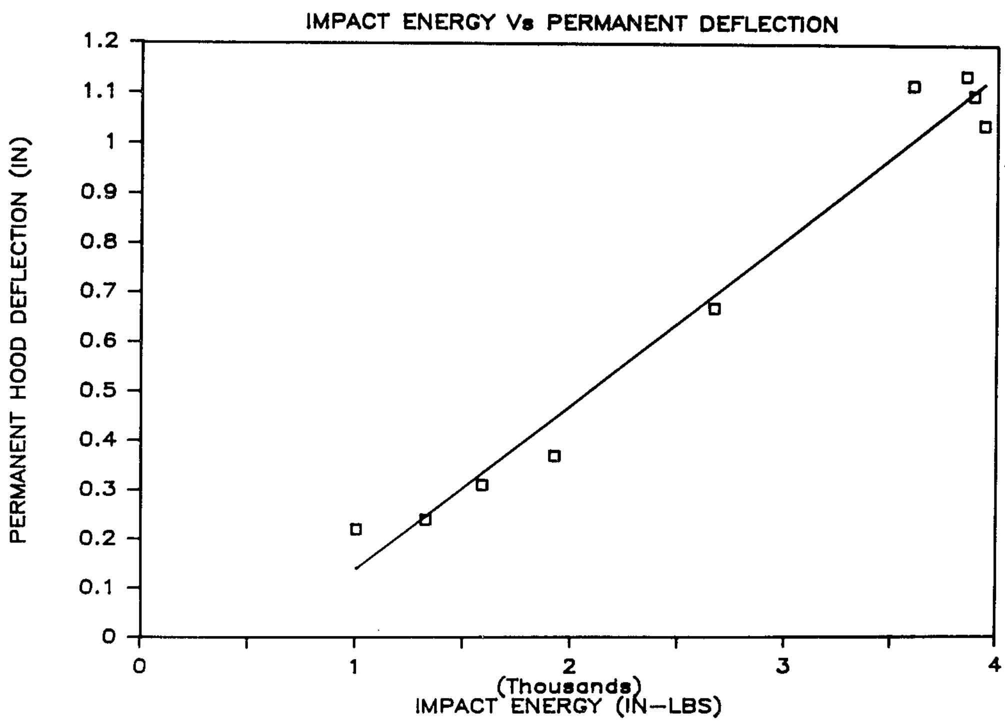

FIGURE 3 -- Relationship Between Impact Energy and Permanent Hood Deformation From SRL-39 Hood Impact Data

There are many different ways of defining a dent; not only is there a localized deformation, but there is a global effect as well. Many of the contour-measuring devices previously used were incapable of defining a global dent due to the lack of a fixed reference for comparison.

A relatively new digital Itek contour measuring device was utilized to measure dents. The cadaver hoods were measured at the maximum head dent location using this device. The contours were taken across the entire width of the hood, with reference points on each fender, giving a contour that was parallel to the bumper. To provide a reference from which to compare global deformations, a new hood was measured in precisely the same position as the test hood for each case. This baseline profile was then compared to the test hood. In order to make numerical and graphical comparisons, a data processing program was developed for the micro-computer that was used in conjunction with the Itek digital measuring device. This program imported the two data files, made the desired calculations, and provided graphs of the baseline and test hood profiles together for comparison. The global deformation was determined by matching up the reference points on the fenders and then calculating the difference between the baseline and test hoods at the point of maximum deformation. Another variation on global deformation involved matching the hood centerlines and the fender reference points on the impacted side of the hood, and then calculating the maximum difference. The purpose of this second method was to try to separate out some of the body effects from the effect of the head impact alone.

To develop and verify a method for determining effective head mass, experimental cadaver head impact reconstructions were conducted, using the variable mass head impactor, to reproduce the individual cadaver hood deformations. To do this, it was necessary to choose an effective head mass with which to begin testing. Several pieces of information were utilized to estimate this mass for a given cadaver test. First, the cadaver hood deformation was measured, as described, even though it was not yet known which method of calculating hood deformation would provide the best definition of head dent. Secondly, the head impact velocity was determined with good accuracy by digitizing the head trajectory in the films of the event. Finally, the linear relationship shown in Figure 3 provided an initial mathematical function which was used to solve for head mass. As shown in Figure 3, the permanent deformation vs. impact energy relationship was characterized in the form,

$$y = m*x + b$$

where,

m = slope of the line

b = the value of y at the point where the line crosses the y axis

and m and b are known values established from the empirical test data. In this relationship, y is the permanent deformation, and x is the impact energy. Impact energy is defined as,

$$x = (1/2)*(\text{mass})*(v**2)$$

With the velocity v known, all that remained was to solve this relationship for the head mass, as shown.

$$\text{mass} = \frac{2*(y-b)}{M*(v**2)}$$

Several reconstruction tests were conducted to reconstruct each cadaver head impact. For each cadaver experiment, the first reconstruction test was run using the method just described to calculate an initial estimate of head mass. With subsequent reconstruction tests the constants m and b in the relationship were established for the particular impact location, to relate impact energy to the global dent measurement as accurately as possible. The definition of hood deformation changed in the course of the testing as it became evident that the global dent measurement included varying amounts of body effects in the different cadaver tests. Some of the cadaver hood global deformations were caused primarily by the head impact and some included the force of a greater portion of the body, depending on the kinematics of that particular impact. Since the intent was to characterize the effective head mass and not the effective body mass, it became necessary to define a "local" head dent measurement. This localized dent provided much more consistent results, and confined the range of head masses to a more reasonable set, with a lower bound of 4 pounds and an upper bound of 13 pounds.

From this reconstruction data it became evident that the deformation-energy relationship was specific to location, even on the same vehicle. For each location it was possible to build a specific relationship from two data points or more. From this, a fairly accurate estimate of head mass could be obtained which would reproduce a known dent at a known velocity. For each cadaver test, at least one reconstruction came close to the final head mass estimate determined from the finished database. The accelerations from these "best" reconstructions were compared to the actual accelerations from the cadaver tests. These comparisons, along with the best estimate of head mass, are shown in Table 1. Although the cadaver test data included some rotational effects and some bad data channels, in most cases the acceleration results agreed fairly well with the accelerations from the best reconstructions.

TABLE 1 -- BEST RECONSTRUCTION RESULTS

CAL-MAN #	RECON #	VELOCITY (MPH)		RECON HEAD MASS (LBS)	LOCAL DEFORMATION (INCHES)		RESULTANT PEAK G'S		HIC		EST. EFF. HEAD MASS (LBS)
		NOM	ACT		RECON	CAL	RECON X	CAL TRIAX	RECON	CAL	
20	173	22.5	23.21	7.94	0.203	0.147	129.3	197	1093	863	7.34
21	72	20.2	23.12	6.15	0.193	0.192	260.0	310	1991	1605	6.44
22	73	19.4	21.20	12.95	0.194	0.162	125.0	122	608	524	12.89
23	179	24.0	24.51	5.55	0.193	0.165	252.3	760 *	2195	6828 *	4.20
24	83	19.1	19.86	13.55	0.187	0.151	102.5	115	644	468	11.78
	85	19.1	20.16	8.75	0.117	0.151	147.5	115	484	468	
26	160	24.4	24.51	7.25	0.188	0.195	233.0	133	1543	439	7.66
27	163	23.5	22.48	13.25	0.274	0.295	126.3	146	826	739	12.96
28	159	23.6	23.50	6.50	0.130	0.112	233.0	815 *	1582	7145 *	4.82

*ACCELEROMETERS COMPROMISED

In this cadaver study, a method for determining effective head mass with a known velocity and local deformation was established. It was also found that when the deformation from a real hood impact was to be measured, the local dent provided the best definition of head impact without including unpredictable and inconsistent body effects.

3.2 Accident Reconstructions

The next step in this phase of work was to relate real-life injury to impactor response in the laboratory. The cadaver tests could not provide sufficient injury information to bridge that gap, whereas accident reconstructions could. Accident cases generally supply injury information, estimates of vehicle impact velocity, circumstances leading up to the accident, some kinematic analysis of the impact, and some measure of permanent deformation. At worst, the permanent deformation can only be estimated from a photograph, at best it can be measured from the actual case hood. Most commonly, the investigator has measured the contour of the dent with a 12 inch contour device, or has estimated the dent depth by some method when examining the vehicle after the accident. Accident cases can potentially provide a wealth of data for many different ages of people and many different injury levels. This current set of accident data was chosen to fill in the gaps in the data that had been previously reconstructed (1,2,3), with a particular emphasis on child accident cases. (The over-representation of child pedestrian accident victims is discussed in References 5 and 10.)

The accident cases used in this study came from two sources. An accident investigation study which took place in the late 1970's was called PICS (Pedestrian Injury Causation Study) and it focused on kinematics and injury as related to vehicle contacts. A later study, PAIDS (Pedestrian Accident Investigation Data Support), was similar to PICS but placed a higher emphasis on collecting data from accidents in which head injuries occurred, as well as putting more effort into collecting dent information and profiles. Most of the cases used for reconstruction in this study were PAIDS cases due to the quality of dent information available, but some PICS cases were reconstructed as well.

Although most of these cases provided estimates of the vehicle impact velocity, the head impact velocity, as well as the effective head mass, still remained to be determined. MADYMO (6) simulations provided an upper bound and a lower bound on the head impact velocity based on the vehicle impact velocity range. Head effective mass for adults could usually be bounded between 5.0 and 13.0 pounds, based on impedance data taken by Stalnaker (7), and by the results of the cadaver test analysis. The method that evolved for determining specific values of velocity and head mass made use of the fact that the deformation vs. energy relationship for any given location could be characterized by a minimum of two data points. A set of baseline tests were run for each accident case. These used the upper and lower bound velocities and head masses to bound the energy of the actual impact, and to determine the specific permanent deformation vs. impact energy relationship for the impact location on each vehicle. Once this relationship was established, the impact energy required to reproduce the actual permanent deformation in the accident could be determined. This is illustrated in Figure 4 for a typical reconstruction case.

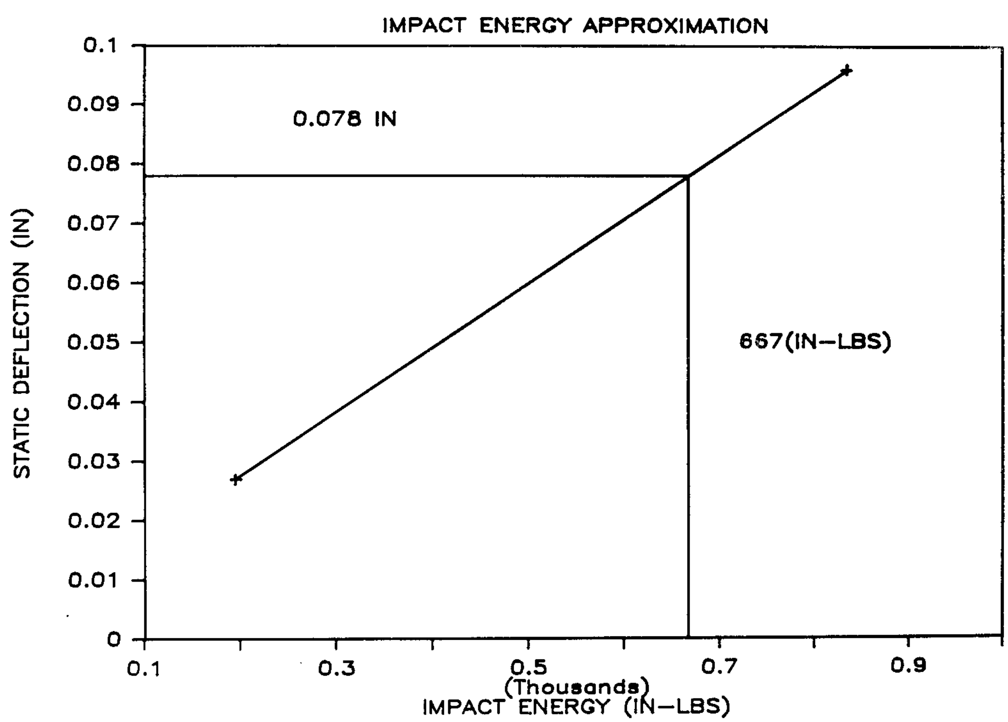

FIGURE 4 -- Method for Determining Accident Impact Energy Based on Vehicle Hood Stiffness Data From Baseline Tests and Known Hood Deformation From Accident Data

If the permanent deformation from the accident case did not fall on the curve within, or reasonably close to, the bounded region, then a re-evaluation was made of the validity of the dent depth observed from the accident case and the reasonableness of the upper and lower bound mass and velocity values.

Next, a mass vs. velocity plot was generated, as shown in Figure 5, using the impact energy required to produce the dent (as was illustrated in Figure 4). (The mass vs. velocity curve is a constant energy line, representing all possible values of mass and velocity which satisfy the desired energy constraint.) In general, as can be seen in Figure 5, superimposing the upper and lower bound mass and velocity values on the constant energy plot resulted in narrowing the acceptable bounds for mass and velocity.

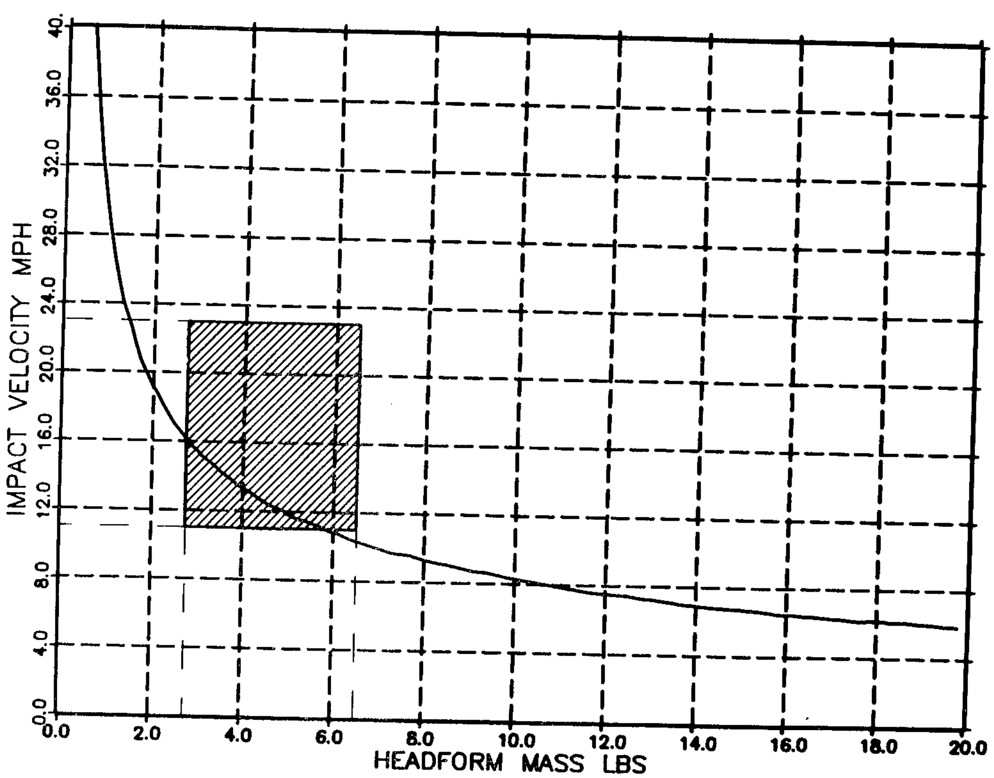

FIGURE 5 -- Constant Energy Curve for PAIDS Case 82-10-201, Illustrating Constraints on Acceptable Bounds for Head Mass and Impact Velocity

The remaining task was to choose one specific mass and velocity combination from among those which fulfilled the energy requirement. An attempt was made to determine whether or not impact momentum could be related to some measurable parameter from each accident case. If such a relationship could have been found (similar to the permanent deformation/impact energy relationship), then a discrete combination of head mass and impact velocity could have been derived. Although earlier test data (4) suggested a relationship between impact momentum and maximum dynamic deformation, this information was of no use, since maximum dynamic deformations from the accident cases were unknown. Consequently, individual values of impact velocity and head mass which produced the desired impact energy were chosen arbitrarily, simply by ratioing momentum and energy similarly between upper and lower bound values.

This was the method generally used to choose values of head mass and impact velocity for reconstruction tests. When either the hood itself or a profile of the head dent was provided so that an accurate and consistent measurement of local deformation could be determined, this method produced accurate reconstructions. In those cases where the value of permanent deformation was only an estimate, particularly one from a photograph, the only judgement that could be made as to the accuracy of the reconstruction was from a visual comparison of the hood dents. This method obviously left some room for error, but generally gave fairly good results. In most of the reconstructions, the deformation results were considered satisfactory. Table 2 shows the accident case data as well as the test data and results for all of the baseline testing and adult reconstruction testing done as described above. Table 3 shows the same information for the child accident cases. This set of child and adult reconstructions in which baseline testing was done will be referred to as Set I.

Another set of child reconstructions was done which retested cases previously reconstructed in SRL-10 or SRL-39. In the SRL-10 and SRL-39 testing, several impacts were made for each accident case to try to reproduce the accident dent. Usually, one impact was selected as the

TABLE 2 - SRL-86 Set I Adult Reconstruction Cases - Baseline and Reconstruction Tests

PAIDS OR PICS #	VEHICLE TYPE	TEST # Q	TEST CODE ***	TEST VELOCITY MPH NOMINAL	TEST VELOCITY MPH ACTUAL	TEST HEAD MASS (LB)	TEST IMPACT ENERGY (IN-LBS)	STATIC DEFORMATION (IN) TEST	STATIC DEFORMATION (IN) CASE	DENT CODE **	ACTUAL AIS	FATAL	AGE	M OR F	HEIGHT (IN)	WEIGHT (LB)
82-08	1980	232	B	25.2	26.57	6.65	1882	0.175	0.219	P						
-205	PONTIAC	233	B	28.4	27.61	6.65	2032	0.211	0.219							
PAIDS	BONNEVILLE	240	R	27.1	27.34	7.65	2292	0.217	0.219		4,4,3	N	22	M	--	--
81-12	1979	221	B	16.0	16.07	6.65	688	0.063	0.125	I						
-207	OLDS	222	B	20.0	19.28	5.55	827	0.116	0.125							
PAIDS	DELTA 88	241	R	18.3	18.06	7.65	1000	0.097	0.125		5,3,3	N	34	F	--	--
81-09	1978	223	B	12.0	11.51	6.65	353	0.088	0.330	E						
-202	FORD	231	B	14.0	14.04	5.55	436	0.135	0.330							
PAIDS	THUNDERBIRD	242	R	14.0	13.97	7.90	618	0.330	0.330		2,0,0	N	89	M	66	130
83-02	1981 FORD	181	B	8.8	8.55	6.65	195	0.027	0.078	P						
-204	MUSTANG	183	B	13.0	13.19	11.95	834	0.096	0.078							
PAIDS	GHIA	243	R	12.9	12.56	10.7	677	0.068	0.078		1,0,0	N	50	M	70	140
81-08	1979 FORD	180	B	20.0	19.68	6.65	1032	0.363	0.125	E						
-207	MUSTANG	182	B	16.0	15.85	6.65	670	0.169	0.125							
PAIDS	GHIA	245	R	16.3	16.63	6.90	765	0.169	0.125		2,1,1	N	18	M	--	--
83-02	1973	224	B	18.4	18.17	6.65	880	0.069	0.094	E						
-201	OLDS	230	B	20.0	20.17	6.65	1085	0.074	0.094							
PAIDS	CUTLASS	252	R	20.5	20.53	7.65	1292	0.090	0.094		4,2,0	N	22	M	70	150
82-07	1979	234	B*	30.0	31.25	6.65	2603	0.295	0.278	H,P						
-203	PONTIAC	235	B	35.0	37.42	7.90	4434	0.331	0.278							
PAIDS	TRANS AM	249	R*	40.0	38.42	7.65	4526	0.423	0.278		4,4,4	Y	24	M	68.5	130
83-03	1978	236	B	27.6	28.30	6.65	2135	1.940	1.440	W,P						
-201	HONDA	256	B	27.0	27.34	6.90	2067		1.440							
PAIDS	ACCORD CVCC	257	R	27.0	26.33	6.90	1917	2.060	1.440		3,2,2	Y	71	F	64	110
82-07	1979	246	B	20.0	20.46	6.65	1118	0.235	0.113	H						
-202	MERCURY	247	B	30.0	30.25	10.05	3686	0.265	0.113							
PAIDS	COUGAR	254	R	20.2	20.31	8.50	1405	0.117	0.113		3,2,1	N	35	M	67	--
82-09	1967	251	B	27.0	25.97	5.55	1500	0.287	0.250	P						
-203	FORD	253	B	21.5	21.54	7.65	1423	0.304	0.250							
PAIDS	THUNDERBIRD	255	R	21.8	21.96	7.65	1478	0.293	0.250		5,4,3	Y	69	F	62	160

*SEE TEXT

**DENT CODE KEY
H = MEASURED FROM ACTUAL ACCIDENT HOOD
P = MEASURED FROM PROFILE OF DENT TAKEN AT ACCIDENT SCENE
I = ESTIMATE MADE BY ACCIDENT INVESTIGATOR
E = ESTIMATE MADE FROM PHOTO OF DENT
W = WINDSHIELD IMPACT RATHER THAN HOOD

***TEST CODE KEY
B = BASELINE
R = RECONSTRUCTION TEST

TABLE 3 -- SRL-86 SET I CHILD RECONSTRUCTION CASES - BASELINE AND RECONSTRUCTION TESTS

PAIDS OR PICS #	VEHICLE TYPE	TEST #	TEST CODE **	TEST VELOCITY MPH NOMINAL	TEST VELOCITY MPH ACTUAL	TEST HEAD MASS (LB)	TEST IMPACT ENERGY (IN-LBS)	STATIC DEFORMATION (IN) TEST	STATIC DEFORMATION (IN) CASE	DENT CODE *	ACTUAL AIS	FATAL	AGE	M OR F	HEIGHT (IN)	WEIGHT (LB)
81-08	1968	39-81	B	16.0	16.0	9.81	1001	0.200	0.063	E						
-202	FORD	39-120	B	9.4	9.4	9.81	347	0.056	0.063							
PAIDS	MUSTANG	39-121	R	12.0	12.0	9.81	566	0.147	0.063							
		172	B	10.0	10.19	5.55	231	0.024	0.063							
		244	R	13.0	12.89	5.55	370	0.036	0.063		2,1,0	N	7	F	52	55
99-07	1978	39-127	B	18.0	18.0	9.81	1271	0.380	0.063	E						
-201	MAZDA	39-129	R	13.0	13.0	9.81	665	0.109	0.063							
PICS	GLC	39-130	B	14.0	14.0	9.81	771	0.191	0.063							
		248	R	14.0	14.01	5.55	437	0.043	0.063		2,1,0	N	7	M	54	72
82-10	1977	225	B	16.8	15.46	5.55	532	0.154	0.094	E						
-201	TOYOTA	229	B	11.0	10.05	5.55	224	0.046	0.094							
PAIDS	CELICA	258	R	13.1	13.29	3.90	276	0.102	0.094		2,2,1	N	2.5	F	25	36
83-01	1969	219	B	18.0	17.83	5.55	707	0.097	0.063	P						
-202	VOLKSWAGEN	220	B	9.0	7.43	5.55	123	0.043	0.063							
PAIDS	BEETLE	259	R	12.1	11.87	3.90	220	0.069	0.063		1,1,1	N	8	M	48	50
82-05	1976	226	B	16.8	16.07	5.55	575	0.062	0.050	E						
-201	OLDS	227	B	14.0	13.54	5.55	408	0.056	0.050							
PAIDS	CUTLASS	228	B	13.0	12.67	5.55	357	0.049	0.050							
	SUPREME	260	R	15.0	13.97	3.90	305	0.044	0.050		2,2,1	N	3	M	39	45

*DENT CODE KEY
H = MEASURED FROM ACTUAL ACCIDENT HOOD
P = MEASURED FROM PROFILE OF DENT TAKEN AT ACCIDENT SCENE
I = ESTIMATE MADE BY ACCIDENT INVESTIGATOR
E = ESTIMATE MADE FROM PHOTO OF DENT
W = WINDSHIELD IMPACT RATHER THAN HOOD

**TEST CODE KEY
B = BASELINE
R = RECONSTRUCTION TEST

best reproduction of the dent, and was labeled the reconstruction for that case. These child accident reconstructions were some of the cases shown in Figure 2 where injury data did not correspond well with test results. As mentioned earlier, this was believed to be because a 9.81 pound head mass was used for all reconstructions.

The retests of these child cases were done using the variable mass head impactor so that an appropriate mass and velocity might be used. For these retests, it was not necessary to run baseline tests because the SRL-10 and SRL-39 tests for each accident case provided the database needed to determine the impact energy and to choose appropriate values for head mass and velocity. Then, the retest was done using the new head mass and velocity combination to provide a more accurate reconstruction with respect to injury correlation. This set of retest reconstructions of cases previously done in SRL-10 and SRL-39 is referred to as Set II.

These completed reconstructions produced a full set of impact response data to be related to the actual accident injury. This leads to the next phase of work, the head injury evaluation.

3.3 Head Injury Severity Scales

Head injuries, as well as other injuries, to pedestrians are described in the accident files, and an Abbreviated Injury Scale (AIS) value is assigned to each. The Abbreviated Injury Scale is an attempt to standardize the language used by physicians, engineers, researchers, and others to rate the severity of injuries. The object of the AIS scale is to allow for comparison of accident data from various sources. The AIS scale has proven to be very effective as a severity scale of individual injuries; the problem is in scaling the overall condition of the victim. Frequently pedestrian accident victims receive several injuries as the result of a single blow to the head.

The AIS value of the most severe head injury may not be sufficient as a measure of overall head injury severity. Many researchers have shown that there are strong relationships between the survival of an accident victim and the number and severity of individual injuries. A recent study of National Accident Sampling System data correlated the three most severe injuries of accident victims with the probability of death (9). A probability of death scale based on the three most severe head injuries may prove to be a better measure of head injury severity. Nevertheless, the value of the most severe head injury is frequently considered to be the overall injury value of the head. Therefore, in this study correlations were examined between measurements made in reconstructing head dents and both probability of death, and overall AIS based on the most severe head injury.

3.4 Head Injury Prediction Models

Two head injury severity prediction models were used in this study, the Translational Mean Stain Criterion (TMSC), and the Head Injury Criterion (HIC). The TMSC (8) was derived from adult human cadaver tests and a lumped-mass mathematical model of the human head. Acceleration-time responses from the cadaver tests were input to the model, which computed strains and strain rates in the brain. The strains and strain rates were then correlated with injury severities measured in the cadaver tests. There are four versions of the model, to evaluate acceleration inputs in four different directions on the head: A-P (anterior-posterior), L-R (left-right), S-I (superior-inferior), and P-A (posterior-anterior). The result is a series of statistically derived equations expressing AIS level as a function of strain, strain rate, and loading direction. The head mass used in the model was ten pounds, approximating the head mass in cadaver experiments.

As previously stated, performing an accident reconstruction test required that the mass and impact velocity of the test head surrogate closely simulate those of the accident victim's head. In the reconstruction tests, headform mass ranged from approximately 4 to 12 pounds. Therefore, a problem arose; reconstruction acceleration-time data were obtained from a head surrogate that did not necessarily weigh ten pounds, and the TMSC performed its analysis assuming a ten pound head mass. It was thus necessary to scale the reconstruction acceleration-time pulse to make it representative of a ten pound headform prior to entering it into the TMSC.

An equal stress/velocity law (11,12,13) was used to scale acceleration and time from the reconstruction tests for input to the injury prediction models as follows:

$$A_{10} = A_r * 1/\lambda_1$$

$$t_{10} = t_r * \lambda_1$$

where

A_{10} = Acceleration scaled to a 10 pound mass

A_r = Acceleration from reconstruction testing

t_{10} = time scaled to a 10 pound mass

t_r = time from reconstruction testing

$$\lambda_1 = \sqrt[3]{\frac{10 \text{ pounds}}{M \text{ pounds}}}$$

and

M_i = Mass of impactor (assumed actual head mass) used in the reconstruction

For each reconstruction test, the program was run in every applicable mode. That is, if the impact appeared to have occurred at an angle that was a combination of the A-P, the L-R, and the S-I directions, the program was run in each of these modes with the acceleration pulse from the reconstruction. The results from each mode were then averaged to duplicate the direction of impact in the accident case. Finally, the AIS prediction from the model was compared to the head injury severity from the accident.

The HIC also accepts the head acceleration-time history as its input, and was also developed primarily from adult human cadaver head masses of approximately 10 pounds. Therefore, in similar manner as for the TMSC, the reconstruction data were scaled before being entered into the HIC.

4.0 RECONSTRUCTION TEST RESULTS

4.1 Data Set Descriptions

The reconstruction and head injury results can be classified into 3 different sets. Set I, as described in Section 3.2, contains those reconstructions done in SRL-86 which each required a set of baseline tests to determine the characteristics of the vehicle hood at the impact location. All but one of this set of reconstructions were PAIDS cases being reconstructed for the first time, most of which had fairly good dent documentation. Table 4 lists the results of these tests in order of reconstruction test number along with the head injury evaluations. These cases include 5 child cases and 10 adult cases.

The second set, designated Set II in Section 3.2, were originally SRL-10 and SRL-39 child reconstructions which were retested in SRL-86. The Set II retests used the effective child head mass instead of the 9.81 pound head mass used in the original tests. These were primarily PICS cases and did not generally provide very good dent documentation. Thus, even with good dent reproduction, the reconstructions of these cases would not be expected to be as accurate as those in Set I. Set II consists of 8 child cases, which are shown with injury evaluation results in Table 5.

TABLE 4 -- SET I - SRL-86 RECONSTRUCTIONS

ACCIDENT CASE NUMBER	RECON. TEST NO.	ADULT OR CHILD	VELOCITY MPH		RECON HEAD MASS (LBS)	RECON IMPACT ENERGY IN-LBS	LOCAL DEFORMATION IN			MAX.ACCEL. G'S		HIC RECON	ACCIDENT A.I.S.		RECON. T.M.S.C.-A.I.S.		
			VEHICLE ACCIDENT	RECONST (TEST)			RECON STATIC	ACC'NT STATIC	DENT CODE**	RECON	NORM'D		3 HI'EST HEAD	MORTALITY RATE HEAD	IMPACT DIR'TION	DIR'AL A.I.S.	RESULT
PAIDS 82-08-205	S86240	A	28-35	27.3	7.65	2292	0.217	0.218	P	237	217	1571	4,4,3	43.0	L-R*	7.8	7.8
PAIDS 81-12-207	S86241	A	20	18.1	7.65	1000	0.097	0.125	I	139	127	512	5,3,3	39.9	L-R*	3.9	3.9
PAIDS 81-09-202	S86242	A	14-16	14.0	7.90	618	0.330	0.313	E	83	77	365	2,0,0	0.9	L-R*	1.6	1.6
PAIDS 83-02-204	S86243	A	8-14	12.6	10.70	677	0.068	0.078	P	126	128	527	1,0,0	0.2	A-P* S-I*	3.0 0.31	1.7
PAIDS 81-08-202	S86244	C	10-15	12.9	5.55	370	0.036	0.063	E	99	82	313	2,1,0	1.2	A-P* L-R*	0 .03	0
PAIDS 81-08-207	S86245	A	20-30	16.6	6.90	765	0.162	0.125	E	160	142	531	2,1,1	1.6	A-P*	2.3	2.3
PICS 99-07-201	S86248	C	15-19	14.0	5.55	437	0.043	0.063	E	115	94	336	2,1,0	1.2	L-R*	0	0
PAIDS 82-07-203	S86234	A	>35	31.3	6.65	2603	0.295	0.278	H, P	423	369	5859	4,4,4	48.4	A-P* L-R*	7.6 8.5	8.1

**DENT CODE KEY
H = MEASURED FROM ACTUAL ACCIDENT HOOD
P = MEASURED FROM PROFILE OF DENT TAKEN AT ACCIDENT SCENE
I = ESTIMATE MADE BY ACCIDENT INVESTIGATOR
E = ESTIMATE MADE FROM PHOTO OF DENT
W = WINDSHIELD IMPACT RATHER THAN HOOD

*IMPACT DIRECTION KEY
A-P = FRONTAL
P-A = POSTERIOR
L-R = SIDE
S-I = TOP

TABLE 4 -- SET I - SRL-86 RECONSTRUCTIONS (Continued)

ACCIDENT CASE NUMBER	RECON. TEST NO.	ADULT OR CHILD	VELOCITY MPH		RECON HEAD MASS (LBS)	RECON IMPACT ENERGY IN-LBS	LOCAL DEFORMATION IN			MAX.ACCEL. G'S		HIC RECON	ACCIDENT A.I.S.		RECON. T.M.S.C.-A.I.S.		
			VEHICLE ACCIDENT	RECONST (TEST)			RECON STATIC	ACC'NT STATIC	DENT CODE**	RECON	NORM'D		3 HI'EST HEAD	MORTALITY RATE HEAD	IMPACT DIR'TION	DIR'AL A.I.S.	RESULT
PAIDS 83-02-201	S86252	A	20-26	20.5	7.65	1292	0.090	0.094	E	185	169	1394	4,2,0	13.1	L-R*	6.5	6.5
PAIDS 82-07-202	S86254	A	20-30	20.3	8.50	1405	0.117	0.113	H	147	139	559	3,2,1	3.1	A-P* L-R*	2.9 3.8	3.4
PAIDS 82-09-203	S86255	A	32-37	22.0	7.65	1478	0.293	0.250	P	172	158	1128	5,4,3	49.6	L-R	6.4	6.4
PAIDS 83-03-201	S86257	A	31-38	26.3	6.90	1917	2.060	1.440	W, P	264	182	657	3,2,2	3.5	L-R* L-R*	6.4 4.5	4.5
PAIDS 82-10-201	S86258	C	15-24	13.3	3.90	276	0.102	0.094	E	188	137	751	2,2,1	2.6	A-P*	3.7	3.7
PAIDS 83-01-202	S86259	C	20-25	11.9	3.90	220	0.069	0.063	P	74	54	202	1,1,1	0.8	A-P*	0	0
PAIDS 82-05-201	S86260	C	18-24	14.0	3.90	305	0.044	0.050	E	199	146	774	2,2,1	2.6	A-P*	3.7	3.7

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TABLE 5 -- SET II - SRL-86 CHILD RECONSTRUCTIONS

ACCIDENT CASE NUMBER	RECON. TEST NO.	ADULT OR CHILD	VELOCITY MPH		RECON HEAD MASS (LBS)	RECON IMPACT ENERGY IN-LBS	LOCAL DEFORMATION IN			MAX.ACCEL. G'S		HIC RECON	ACCIDENT A.I.S.		RECON. T.M.S.C.-A.I.S.		
			VEHICLE ACCIDENT	RECONST (TEST)			RECON STATIC	ACC'NT STATIC	DENT CODE**	RECON	NORM'D		3 HI'EST HEAD	MORTALITY RATE HEAD	IMPACT DIR'TION	DIR'AL A.I.S.	RESULT
PAIDS 81-08-211	S86261	C	19-22	13.8	3.90	298	N/A	0.188	E	194	142	487	1,0,0	0.2	P-A* L-R*	0.05 3.09	1.6
PICS 19-08-206	S86262	C	20	18.4	3.90	529	N/A	0.250	I	369	270	1661	2,1,0	1.2	A-P* L-R*	4.3 5.28	4.8
PICS 87-12-208	S86263	C	19	16.4	3.90	420	N/A	0.125	I	383	280	2587	3,3,1	4.6	L-R*	6.2	6.2
PICS 68-05-201	S86264	C	10-15	12.8	4.10	269	N/A	0.125	E	129	96	251	2,1,0	1.2	A-P* L-R*	0.62 1.06	.84
PICS 88-07-209	S86266	C	9	16.3	5.3	564	N/A	0.125	I	130	105	423	1,0,0	0.2	P-A*	0	0
PICS 79-06-201	S86268	C	15	17.5	5.30	651	N/A	0.094	I	141	114	518	1,0,0	0.2	A-P*	2.86	2.9
PICS 99-07-201	S86269	C	15-19	17.1	5.80	680	N/A	0.063	E	145	121	343	1,0,0	0.2	A-P* L-R* S-I*	1.17 1.52 0	.90
PICS 87-11-211	S86271	C	40-45	26.0	4.10	1110	N/A	0.250	I	227	169	1900	4,4,0	30.1	A-P* L-R*	6.37 7.45	6.9

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The third set of data has not been previously discussed because it does not include any recent reconstructions. Rather, the data from all other SRL-10 or SRL-39 reconstructions of PICS and PAIDS accident cases were gathered and evaluated. Dent information of these cases was fair to good, and all of the reconstructions were done with a 9.81 pound head mass. Of these cases, 4 were considered to be child cases and 8 were adult cases. The adult cases are considered good reconstructions and are included to provide additional reconstruction data. These cases and their respective head injury results are shown in Table 6 and will be distinguished as Set III.

4.2 Discussion of Specific Cases

Conclusions to be drawn from this study clearly depend upon the accuracy of the reconstructions. Some of the cases listed in Tables 4 and 5 were particularly difficult to reconstruct or had unusual circumstances which resulted in questionable accuracy. None of these were included in the figures which follow or in the data sets used to draw correlations between accident injury severity and reconstruction results. The questionable reconstructions were retained in Tables 4-6 for completeness only. These cases are discussed below by reconstruction test number.

There were only four questionable reconstructions from the Set I cases (Table 4). In two cases, the dent depth was known to a high degree of accuracy but there were unusual circumstances. The first of these was test #257, which represented a difficult case to reconstruct because the accident involved a windshield impact. The characteristics of a windshield are apparently different enough from those of a hood that the method of predicting the correct impact energy to reproduce the dent did not work as well. It is possible that the deformation-energy relationship is only applicable to sheet metal, but this set of reconstructions did not contain enough windshield cases to make a definite determination. Thus the resulting dent in the windshield of test #257 was significantly different from the windshield dent in the

TABLE 6 -- SET III - SRL-10 AND SRL-39 RECONSTRUCTIONS EVALUATED WITH HEAD INJURY CRITERIA

ACCIDENT CASE NUMBER	RECON. TEST NO.	ADULT OR CHILD	VELOCITY MPH		RECON HEAD MASS (LBS)	RECON IMPACT ENERGY IN-LBS	LOCAL DEFORMATION IN			MAX.ACCEL. G'S		HIC RECON	ACCIDENT A.I.S.		RECON. T.M.S.C.-A.I.S.		
			VEHICLE ACCIDENT	RECONST (TEST)			RECON STATIC	ACC'NT STATIC	DENT CODE**	RECON	NORM'D		3 HI'EST HEAD	PROB.OF DEATH HEAD (%)	IMPACT DIR'TION	DIR'AL A.I.S.	RESULT
PICS 67-11-206	S39015	A	40	25.5	10.3	2685	N/A	2-4	I	331	334	2613	5,5,1	58.0	L-R*	7.41	7.41
PICS 78-08-209	S10RRE	A	30-35	29.4	9.81	3399	1.70	0.5-2	I	233	231	3281	6,5,2	100.0	L-R*	8.27	8.27
PICS 78-03-211	S39013	A	27-30	19.6	9.81	1511	0.55	<0.5	I	160	159	1137	4,2,1	14.7	A-P*	5.16	5.16
PICS 79-08-219	S39056	A	25	24.9	9.81	2433	0.75	0.50	I	238	237	1403	5,1,1	27.3	L-R*	5.84	5.84
PICS 19-05-220	S39109	A	15	12.6	9.81	624	0.44	0.30	I	134	133	785	1,1,0	0.3	A-P*	4.07	4.07
PICS 87-08-215	S39135	A	16	22.5	9.81	1991	0.50	0.75	I	209	208	1071	2,1,0	1.2	P-A*	2.93	2.93
PAIDS 82-03-201	S39090	A	15-25	16.2	9.81	1032	1.18	<1.5	E, W	153	152	187	2,1,0	1.2	L-R*	0.65	0.65
PAIDS 81-08-206	S39145	A	24-28	16.7	9.81	1097	1.28	<1.5	E, W	189	188	832	1,0,0	0.2	P-A* L-R*	0.58 3.42	2.00
PICS 88-01-203	S10MRC	C	20-25	21.0	9.81	1734	0.07	<0.5	I	278	277	1407	1,0,0	0.2	P-A* L-R*	3.73 6.41	5.07
PICS 10-01-216	S39052	C	15-20	15.7	9.81	969	0.69	0.25	I	156	155	470	1,0,0	0.2	A-P* S-I*	2.46 0.27	1.37
PICS 68-05-212	S10CR1	C	25	24.0	9.81	2265	0.50	<0.5	I	262	260	1332	2,1,0	1.2	A-P* S-I*	5.45 2.75	4.10
PAIDS 81-08-204	S39091	C	20-30	20.7	9.81	1685	0.23	0.19	E	169	168	864	2,1,1	1.6	A-P* L-R*	3.98 4.82	4.40

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accident case, but it was the best reconstruction achieved for that case.

The second case where testing did not satisfactorily reconstruct the accident used one of the baseline tests, test #234, for the "reconstruction" test. The actual hood from this accident was not available for measurement prior to running the first attempt at a reconstruction test. There was, however, a profile taken from the hood at the accident scene which was used to determine dent depth for reconstruction testing. Unfortunately, a character line in the profile was not distinguishable. This character line distorted the apparent dent in the accident profile such that the dent appeared larger than it actually was. The impact of the first reconstruction test, which reproduced this apparent deformation, was substantial enough to damage the firewall and other substructures in the vehicle. Subsequently, the actual hood from the accident was obtained, and it was learned that the accident dent was considerably smaller. Another reconstruction test was not possible, however, since damage to the vehicle from the first rendered the car unusable for further testing. On reexamination, one of the baseline tests (#234) was determined to best approximate "reconstruction" since the dent from this test most closely reproduced the accident damage. Test #234 was done with a head mass which was approximately one pound too light.

In the third case determined not to be a really good reconstruction, test #255 was selected as the "reconstruction" test. In this case, the vehicle is near classification as an "antique." Hoods for the vehicle were not available from the original equipment manufacturer; as a result, hoods had to be purchased from junk yards. The supply of good hoods for use in reconstruction testing was simply exhausted before we satisfactorily reproduced the accident damage.

A fourth case in Set I deserves special mention. The reported velocity and the photo estimated hood deformation in the accident case reconstructed by test #241 did not support the degree of pedestrian injury which resulted, suggesting that the hood deformation may have changed before the accident data was collected. Although the reconstruction appeared by the comparison of photographs to have adequately reproduced the dent, the impactor response indicated a much lower level of injury than actually occurred in the accident. This was confirmed by each of the head injury predictions. Either the accident data was incorrect, the dent depth was misleading from the photograph, or an injury mechanism was present that at this point we can not reproduce.

In the Set II reconstructions, shown in Table 5, there are a few cases worth mentioning. Reconstruction #271 represents another case in which the deformation did not seem to reflect the level of injury. In this case the head impact occurred at the top front edge of a pickup truck hood which had a very defined front edge corner. There was not only a dent on the top of the hood just beyond the corner edge, but there was another dent on the front edge of the hood, just below the larger dent. One possibility is that the head or shoulder impacted the front of the hood immediately prior to the head impact on the top of the hood, causing a stiffening of the area that the head subsequently impacted, so that the dent produced was much smaller than would be expected at the reported impact speed. The same problem was encountered in the original SRL-39 reconstruction of this case, and the best results were achieved when two impacts were used to reproduce the damage: one horizontal and one vertical, which in combination reproduced the two dents described. Although it was not clear what to do with HIC and normalized G's in this case, MSC theory provides that the sum of the two AIS values should suffice, since a second impact would add additional mean strain-induced injury. This, of course, assumes that both dents were caused by head impacts, which is not clear. Because of this, a different tack was taken in the retest of this case. The retest attempted to reproduce only the dent on the top of the hood to determine the required head mass and velocity. However, comparison of the resulting dent to photographs from the case indicated that the apparent accident dent could not be reproduced with the velocity or head mass within a reasonable range of the reported circumstances. In spite of this, the injury level suggested from the reconstruction shows fairly good correlation to the actual injuries even though the retest dent was somewhat larger than the actual dent. This tends to support the possibility that the hood area was stiffer in the actual accident due to a double hit phenomena than it would have been in the laboratory when a single impact was reconstructed.

In two cases, the retest results indicated injuries higher than those that actually occurred. These are tests #262 and #263. Both were reconstructions of child accident cases in which the lightest head mass (3.9 lbs.) was used, and in which the impact occurred on very stiff structures of the respective hoods. Both resulted in very high peak accelerations in very short time-duration acceleration pulses. Reasons for these outliers in the injury correlations are not completely clear, although the impact position of these tests are among the stiffest structures struck in the reconstruction testing.

4.3 Head Injury Correlations - Reconstruction Results

Correlations were drawn between reconstruction results and accident injury severity using 14 adult cases: 6 from the Set I reconstructions and 8 from Set III. Child cases were not used in deriving the injury relationship because injury severity values were not as evenly distributed, all of the data being at the lower end of the injury severity scale. Data from these 14 reconstruction tests (acceleration, displacement vs. time, and time intervals of HIC calculation) are contained in Appendix A.

4.3.1 Translational Mean Strain Reconstruction Results -- Reconstruction test results in the form of Mean Strain calculations were plotted with accident injury severity. The Translational Mean Strain model output is a calculated value of injury. The model output is on a continuous scale, rather that the discrete values. It is clear that the actual variations in the TMSC have some meaning on a continuous scale, so the model output was used without limiting TMSC predicted injury scale to discrete values.

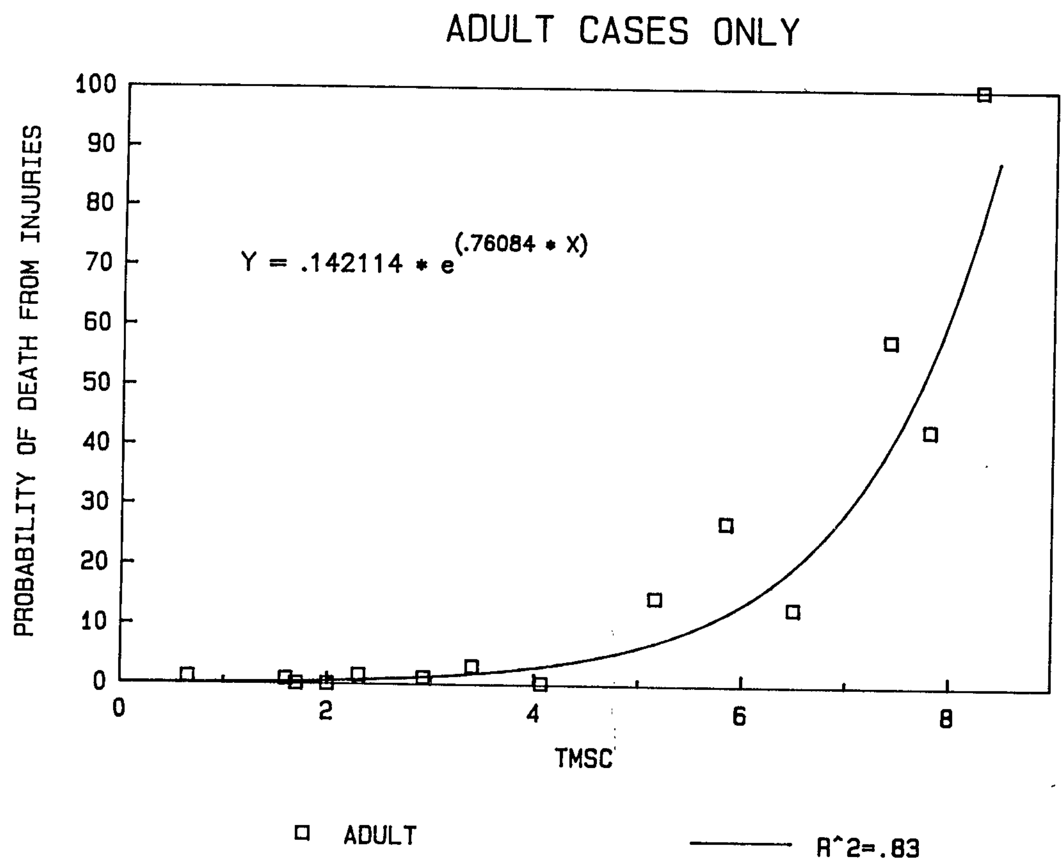

FIGURE 6 -- TMSC Reconstructions -- Normalized TMSC Versus Probability of Death (Adults Only)

Probability of death or mortality rate based on the three most severe head injuries was used first as the accident injury severity scale. Figure 6 shows the results of plotting Mean Strain calculated injury scale values with corresponding probability of death values for the adult cases. An exponential regression line was fitted to this data, and the correlation is excellent. The coefficient of determination for the exponential regression line is 0.83. This indicates that more than 83 percent of the variation in probability of death (Y) is exponentially related with variation in the Mean Strain predicted injury scale (X) described by the regression line

$$Y = 0.142 * e^{(0.761 * X)}.$$

There is a clear increase in probability of death with increasing values of Mean Strain predicted injury scale. There is a threshold near the TMSC predicted injury scale of 5, below which probability of death values are less than 5%, and above which they exceed 5%.

The child accident reconstruction results are added to the adult data in Figure 7. Because none of the child cases involved severe injuries, they do not contribute to defining the correlation between reconstruction results and accident injury severity. Nonetheless, the child data points cluster around the lower end of the curve and appear to conform with the correlation derived from the adult cases.

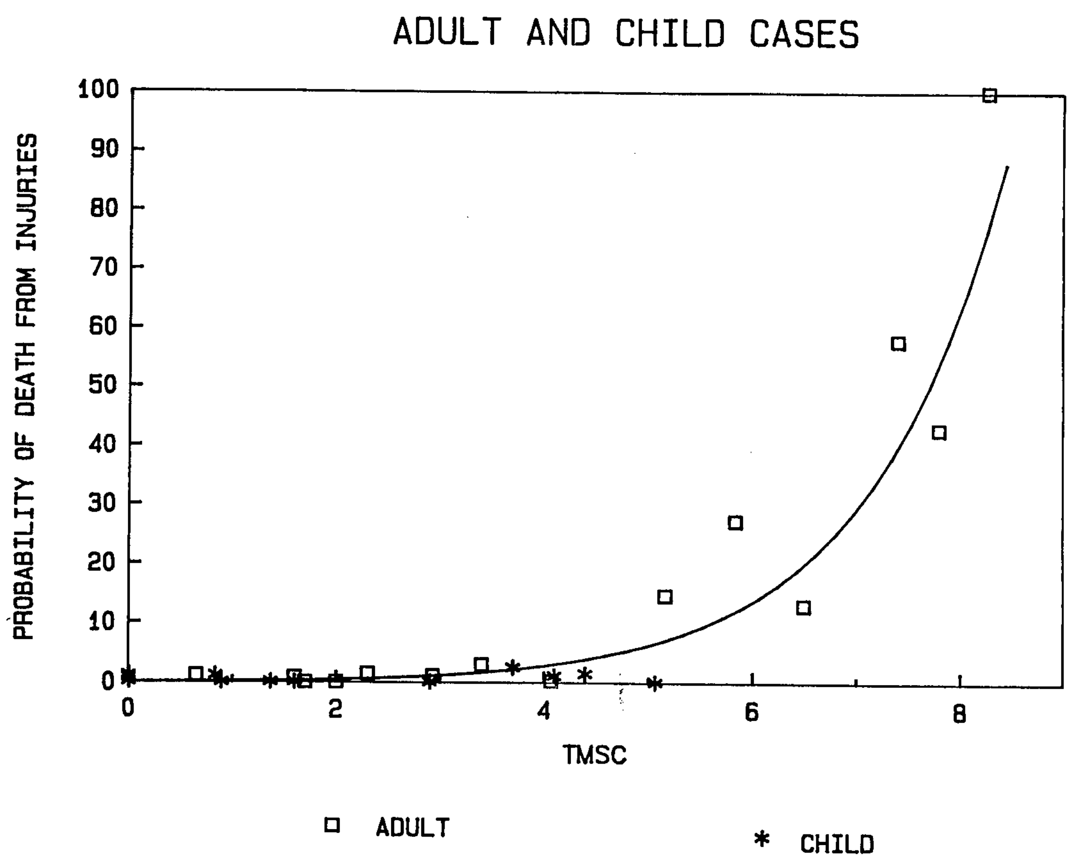

FIGURE 7 -- TMSC Reconstructions -- Normalized TMSC Versus Probability of Death

Next, overall AIS of the accident victim's head injuries were plotted with Mean Strain predicted injury scale values from the reconstruction tests. The results of the adult reconstructions are shown in Figure 8 along with a linear regression line fitted to this data. The coefficient of determination of the linear regression line fit to this data is 0.75, which indicates that 75 percent of the variation in overall

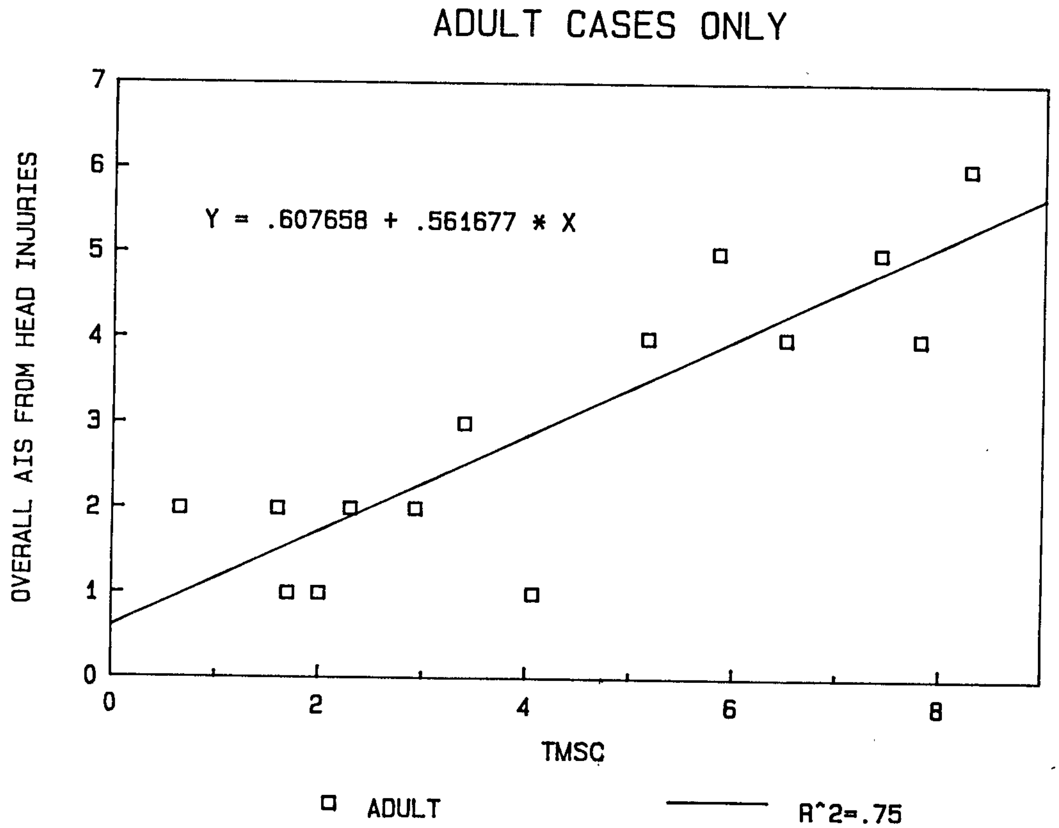

FIGURE 8 -- TMSC Reconstructions -- Normalized TMSC Versus Overall Head AIS (Adults Only)

head injury AIS (X) is linearly related to variation in the Mean Strain model's predicted injury scale values (Y) as described by the regression line

$$Y = 0.608 + 0.562 * X.$$

The coefficient of determination is less than that for probability of death vs. TMSC (Figure 6) due to the fact that the overall head injury AIS scale is not continuous, but is made up of discrete integer values. Given this fact, the linear curve fit of Figure 8 is considered good.

The overall ais vs. TMSC data contained in Figure 8 can be used to estimate the probability of receiving an injury greater than a given severity from a known TMSC value. This is described in Appendix B.

The child accident reconstructions are added to the graph in Figure 9. The child cases conform reasonably well.

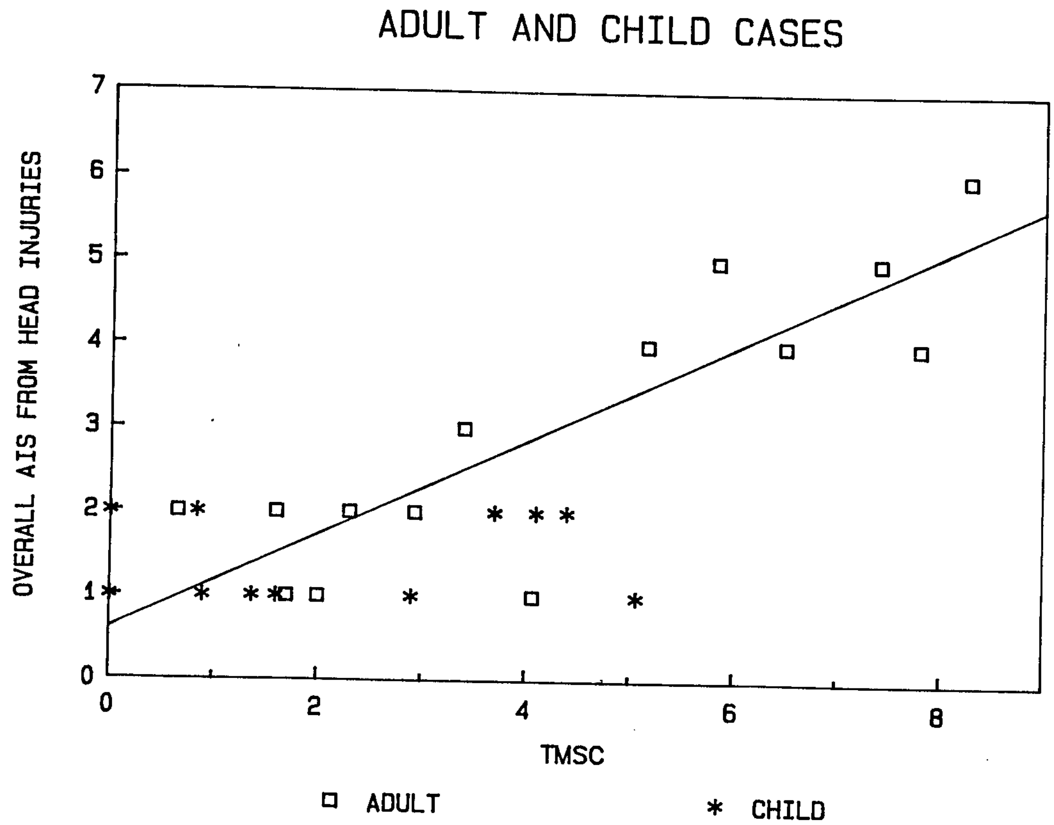

FIGURE 9 -- TMSC Reconstructions -- Normalized TMSC Versus Overall Head AIS

<u>4.3.2 HIC Reconstruction Results</u> -- Reconstruction test results in the form of HIC calculations were plotted with accident injury severity. Probability of death or mortality rate was the first accident injury severity scale used. This information on adult cases is shown in Figure 10 together with a piecewise linear curve fit applied to two sections of the data. The coefficient of determination is 0.94. Ninety-four percent of the variation in probability of death (Y) is linearly attributable to variation of the HIC (X) as described by the regression lines

$$Y = 0.563 + 0.00197 * X, \; X \leq 882.$$

and

$$Y = -31.7 + 0.0386 * X, \; X \geq 882.$$

The first section of the bi-linear curve was defined using the first five data points. The second section of the curve was defined using the remaining nine data points. The two lines intersect at HIC = 882. The data points indicate a very definite rise in probability of death when the HIC exceeds a value of 1000.

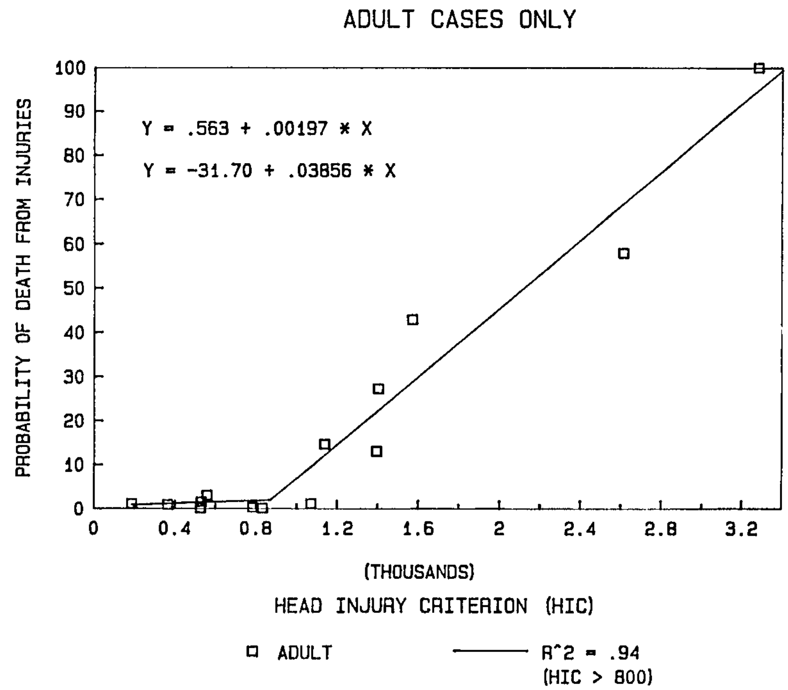

FIGURE 10 -- HIC Reconstructions -- Normalized HIC Versus Probability of Death (Adults Only)

The child accident reconstruction cases are added to the graph in Figure 11. The addition of these cases does not detract from observations made from the adult cases.

Next, HIC values calculated from the reconstruction tests were plotted with overall AIS of the accident victim's head injuries. The results are shown in Figure 12 accompanied by a linear regression line fit to this adult data. For this curve fit, the coefficient of determination was 0.68. This correlation shows a clear relationship between accident injury severity (overall head AIS) and reconstruction results (HIC). The coefficient of determination is less than that for probability of death (Figure 10), probably because of the discrete integer values assigned to the overall head AIS. Notwithstanding this fact, 68 percent of the variation in overall AIS of head injuries (Y) is linearly related with variation in the HIC (X) as described by the regression line

$$Y = 1.175 + 0.00157 * X.$$

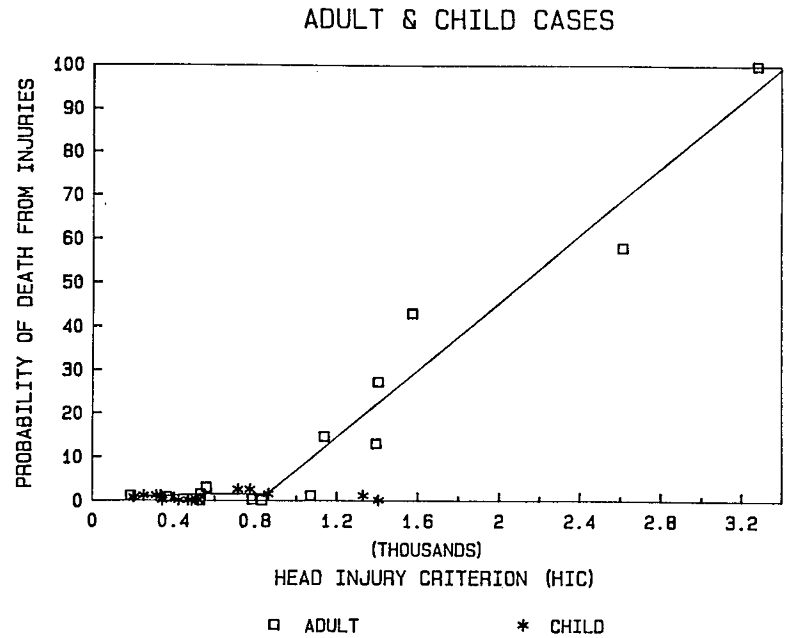

FIGURE 11 -- HIC Reconstructions -- Normalized HIC Versus Probability of Death

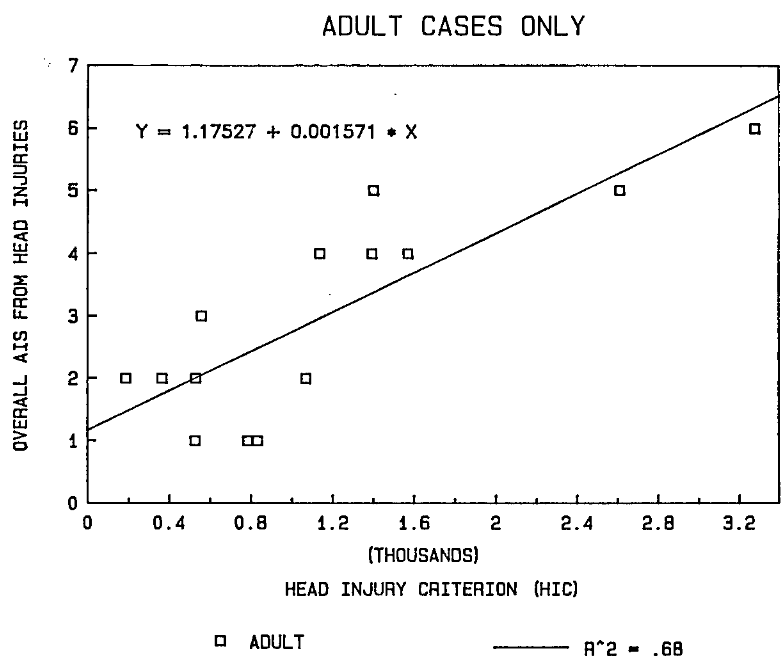

FIGURE 12 -- HIC Reconstructions -- Normalized HIC Versus Overall Head AIS (Adults Only)

A threshold value of HIC ≈ 1100 is evidenced by the fact that above this value, all injury severities are greater than AIS 3, and below this value, all injury severities are AIS 3 or less.

Appendix B contains estimates of the probability of receiving an injury greater than a given severity as a function of HIC, derived from the data presented in Figure 12.

The child accident cases are added to the plot in Figure 13.

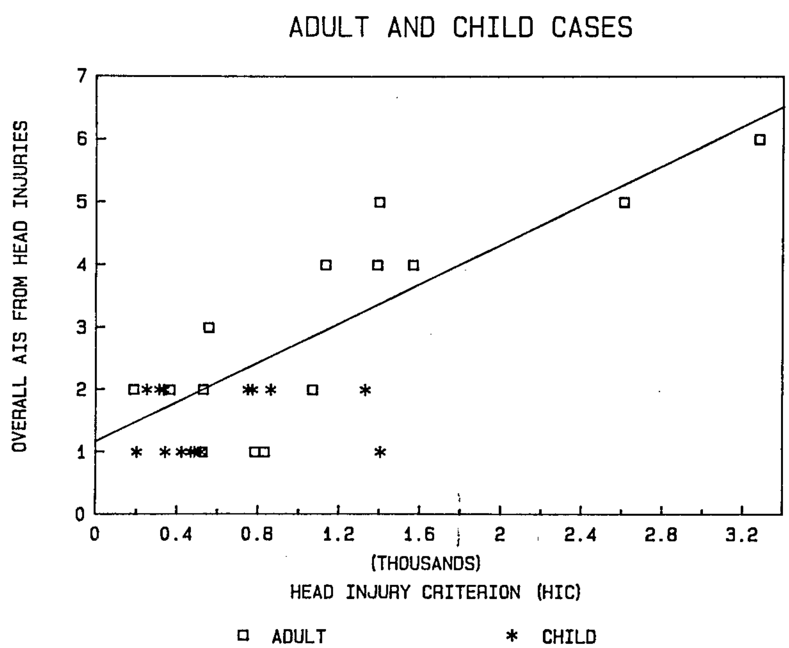

FIGURE 13 -- HIC Reconstructions -- Normalized HIC Versus Overall Head AIS

5.0 CONCLUSIONS

Test results from pedestrian head impact simulations indicate that reconstruction of head impacts is an excellent alternative for developing test devices, test procedures, and injury criteria. The test device, test procedures, and injury prediction models used in this study produce excellent correlation with real world accident injury severity. These correlations are impressive given the imprecision of accident data, the expected variations in human tolerance, the simplifying assumptions used in the reconstruction methodology, and the relatively small sample of accidents which were reconstructable.

The Translational Mean Strain model predicts variations in pedestrian accident head injury severity very well. Eighty-three percent of the variation in probability of death, based on multiple head injuries, is related to variations in the Translational Mean Strain model's predictions of injury in one regression. The variations in overall AIS, based on the single most severe head injury, are also well correlated with variations in the TMSC model's predictions. The reduced correlation here is probably due to the fact that overall accident AIS is described by discrete integer values, and to the fact that overall injury is better determined from multiple injuries than from the single most severe injury.

The Head Injury Criterion model also predicts pedestrian head injury severity very well. Using one bi-linear regression, over 94% of the variation in probability of death is related to variation in the HIC model's calculated values. The HIC model also predicts variation in overall head AIS with a good degree of correlation given the nature of overall accident AIS values.

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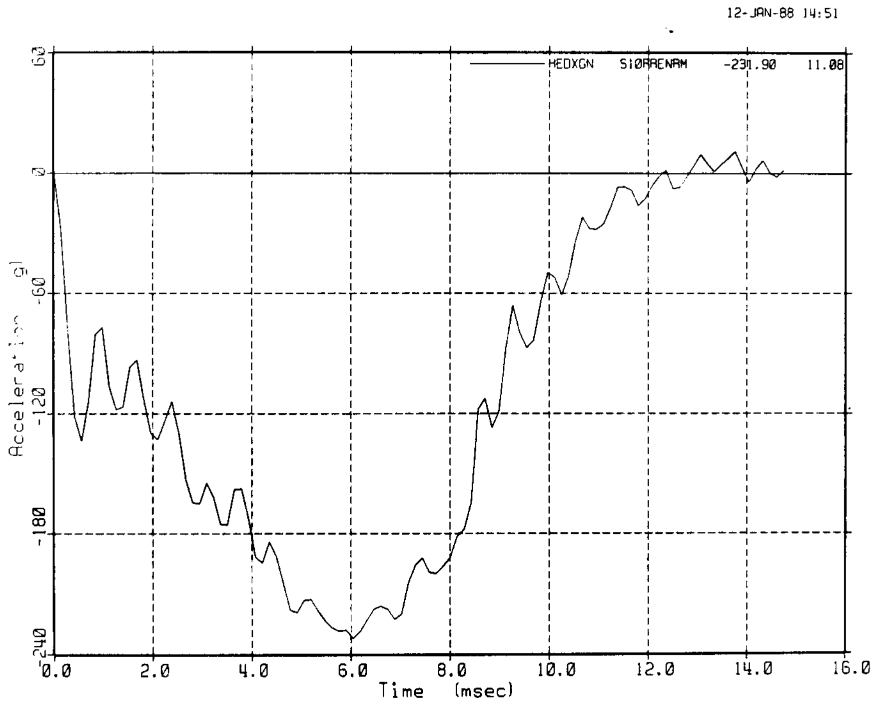
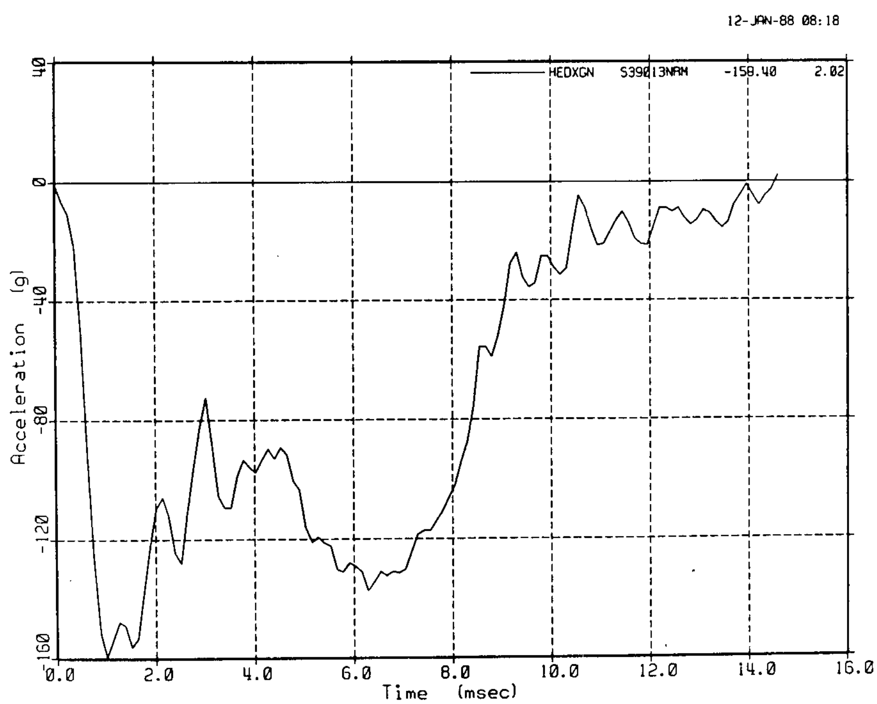
APPENDIX A

Pedestrian Head Impacts Reconstructed

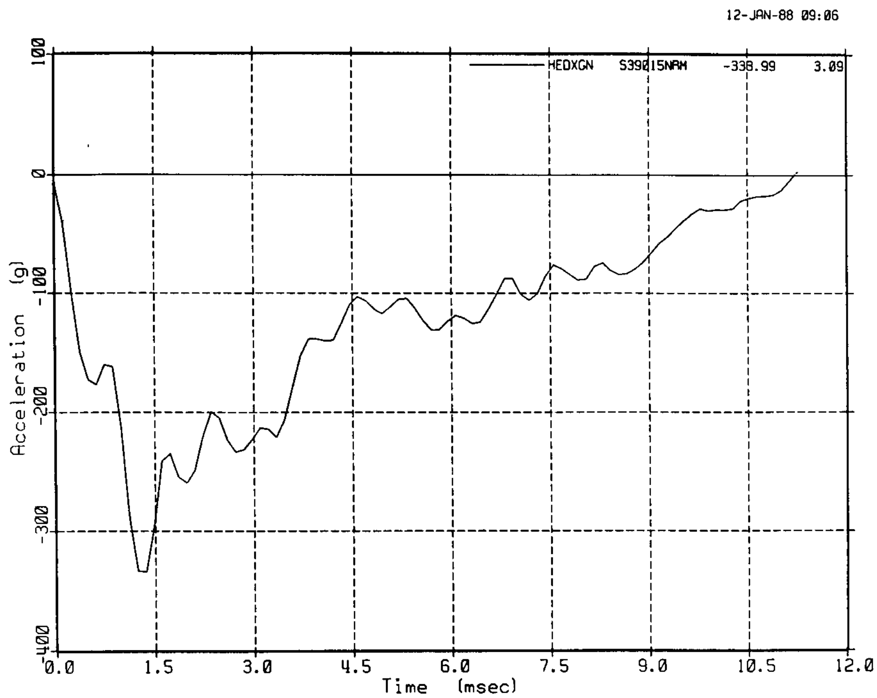
TEST NUMBER	START TIME	END TIME	HIC
S10RRE	1.83	8.99	3281.00
S39090	0.25	21.89	187.00
S39013	0.50	8.43	1137.00
S39015	0.25	6.69	2613.00
S39056	0.50	3.90	1403.00
S39109	1.51	6.16	785.00
S39135	0.63	6.54	1071.00
S39145	0.50	3.15	832.00
S86240	0.63	12.99	1571.00
S86242	0.81	12.03	365.00
S86243	3.67	8.43	527.00
S86245	0.99	12.45	531.00
S86252	0.96	9.57	1394.00
S86254	1.06	6.07	559.00



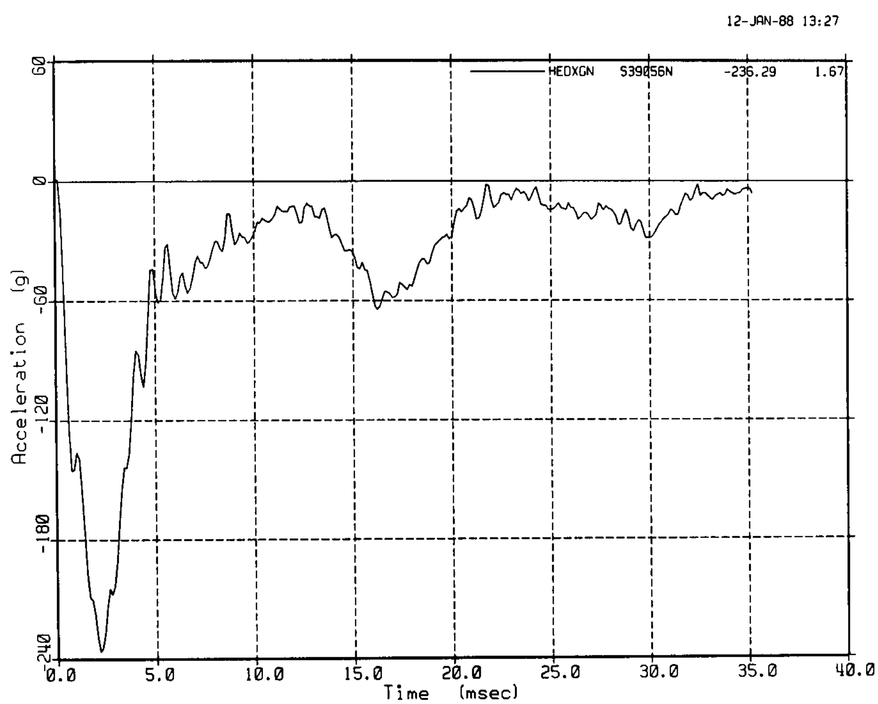
S10RRE



S39013



S39015



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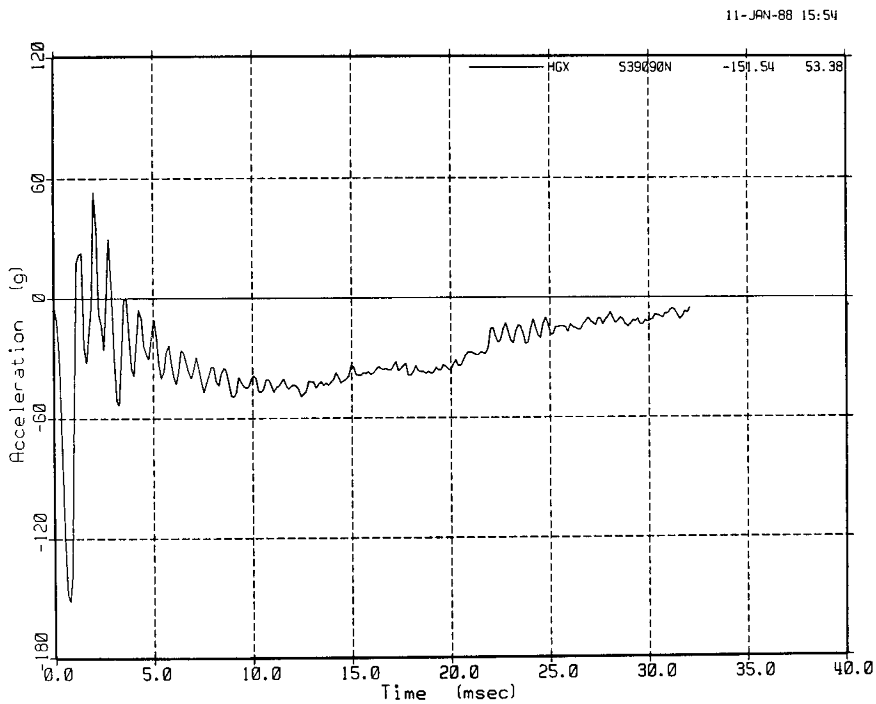

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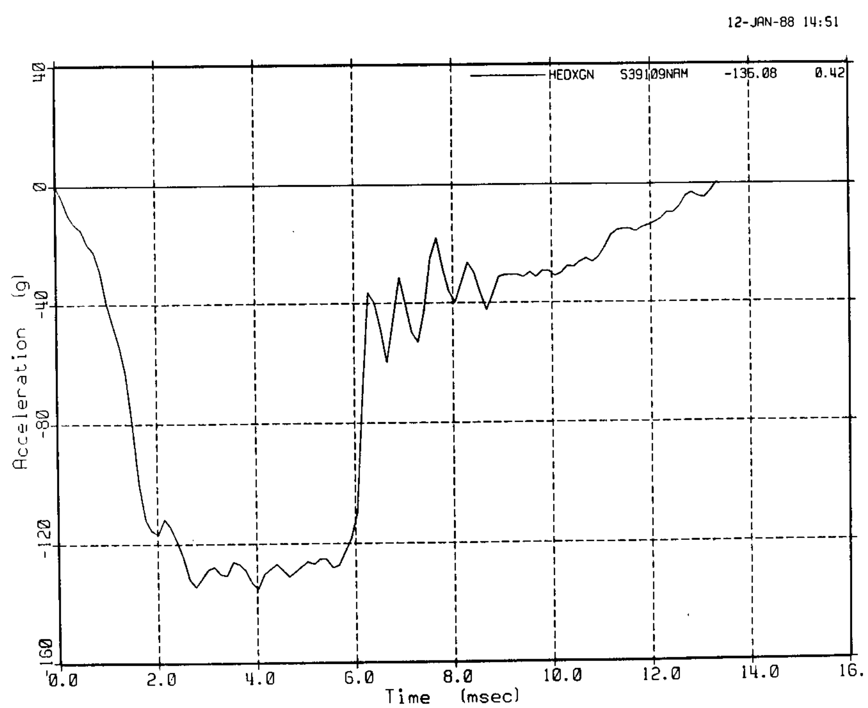

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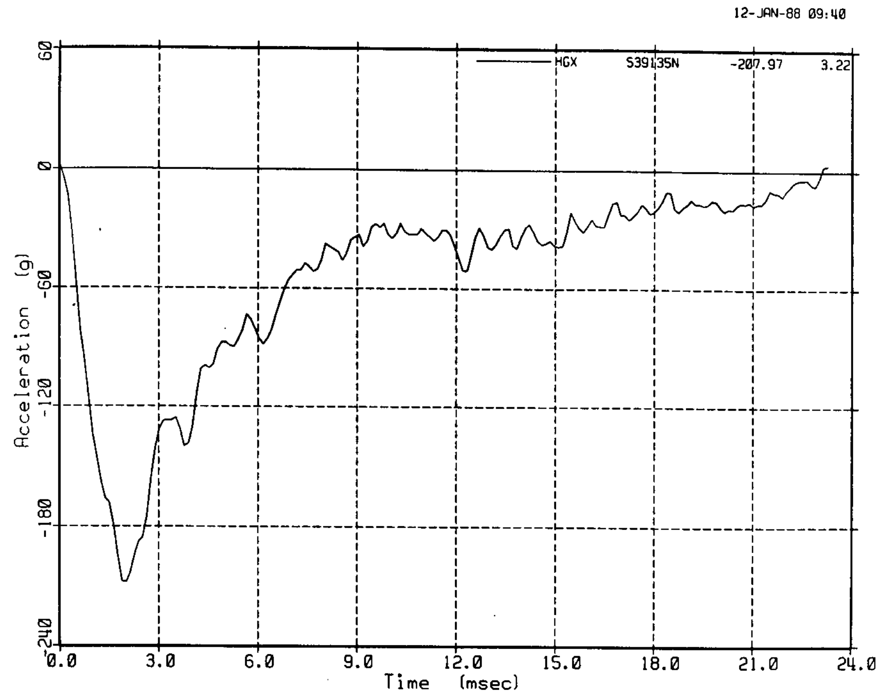

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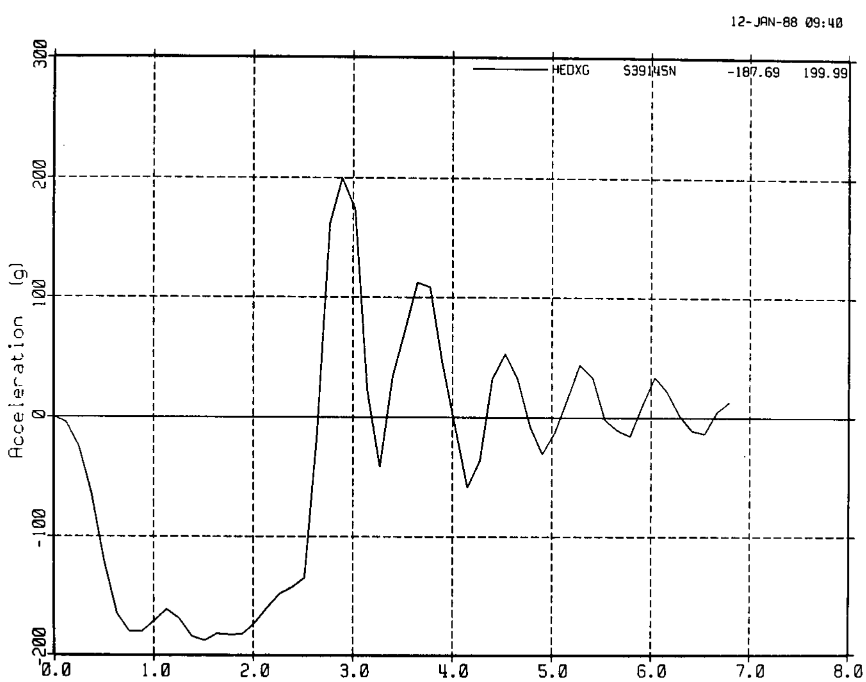

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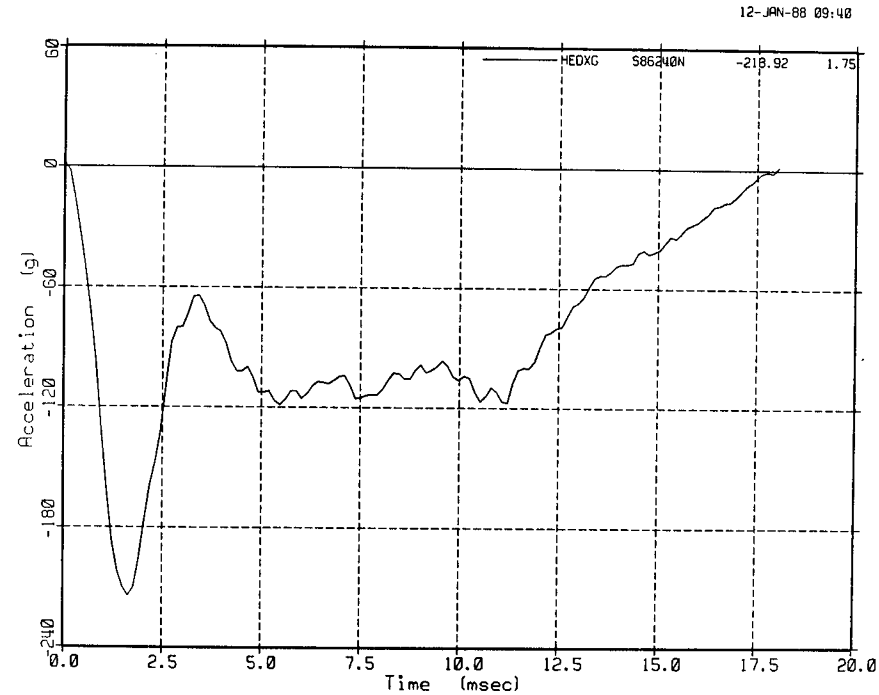

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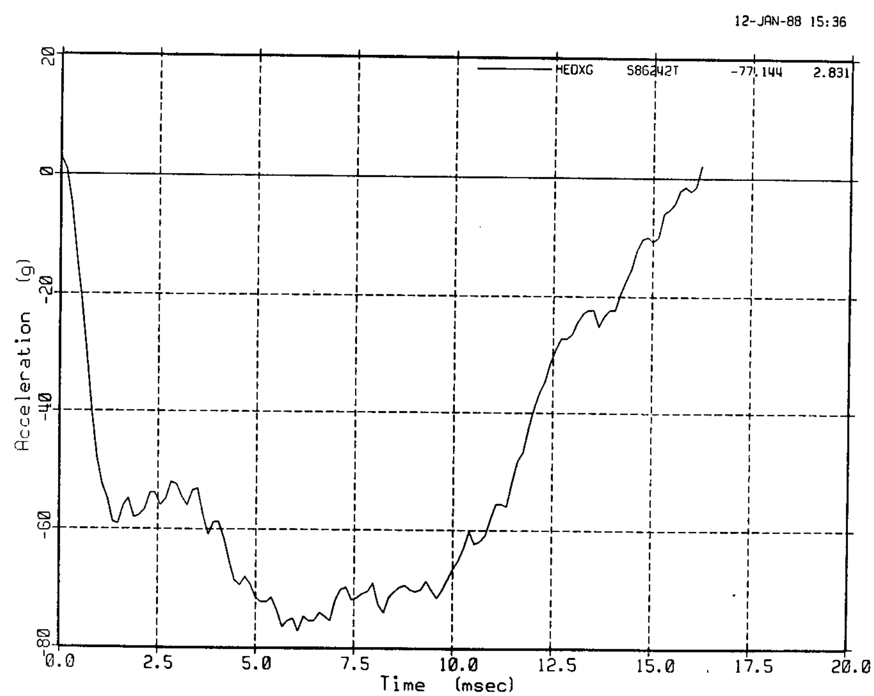

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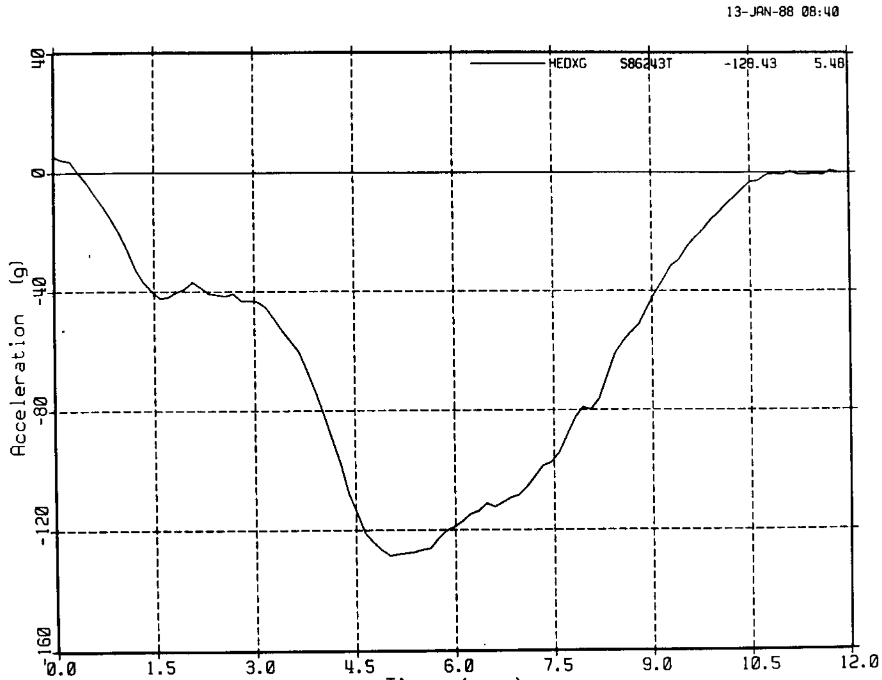

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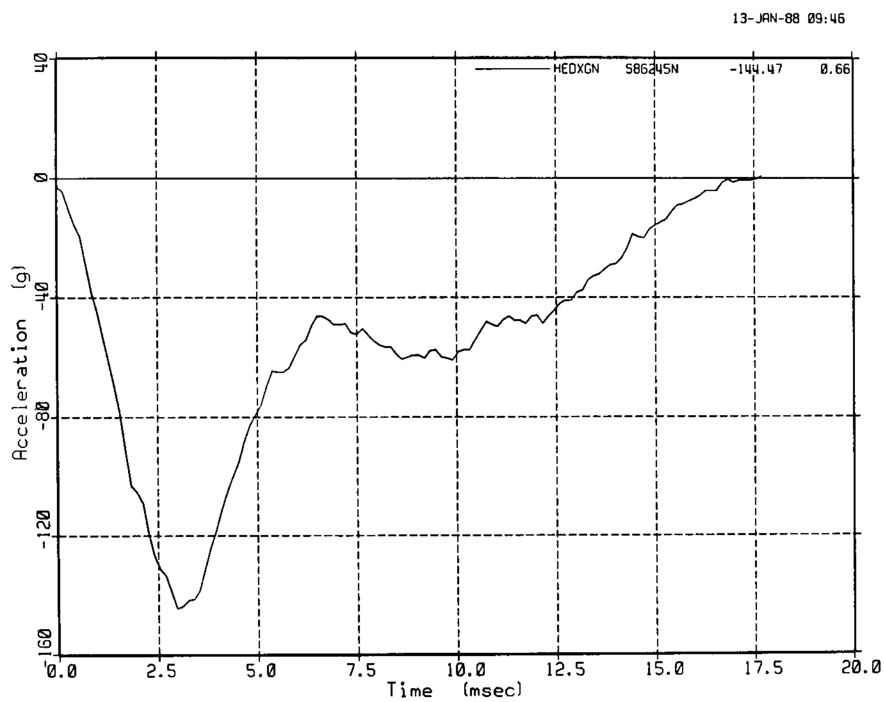

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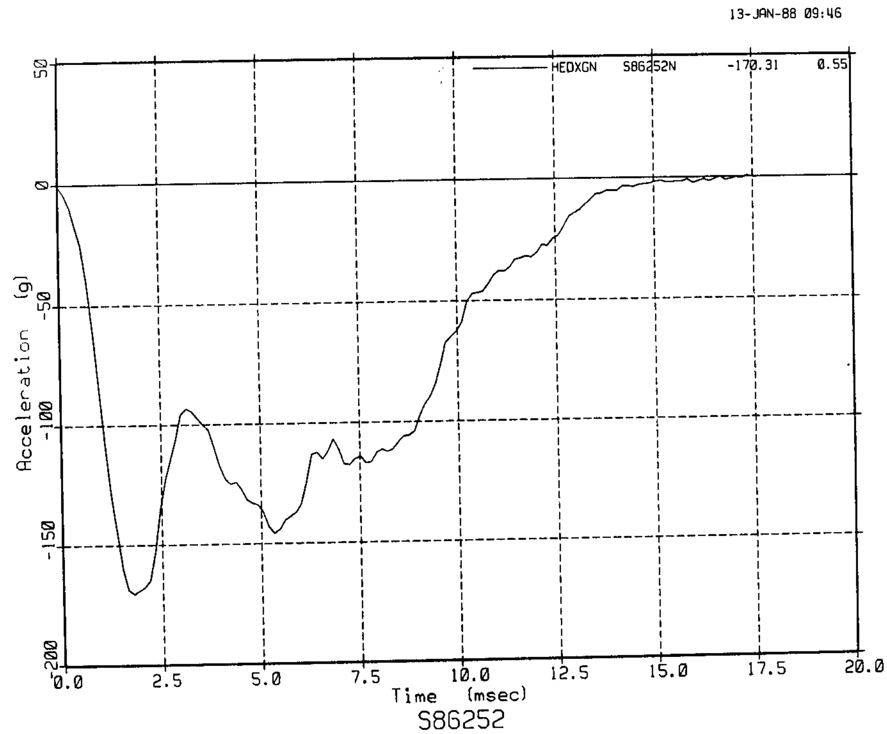
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-50
-100
-150
-200
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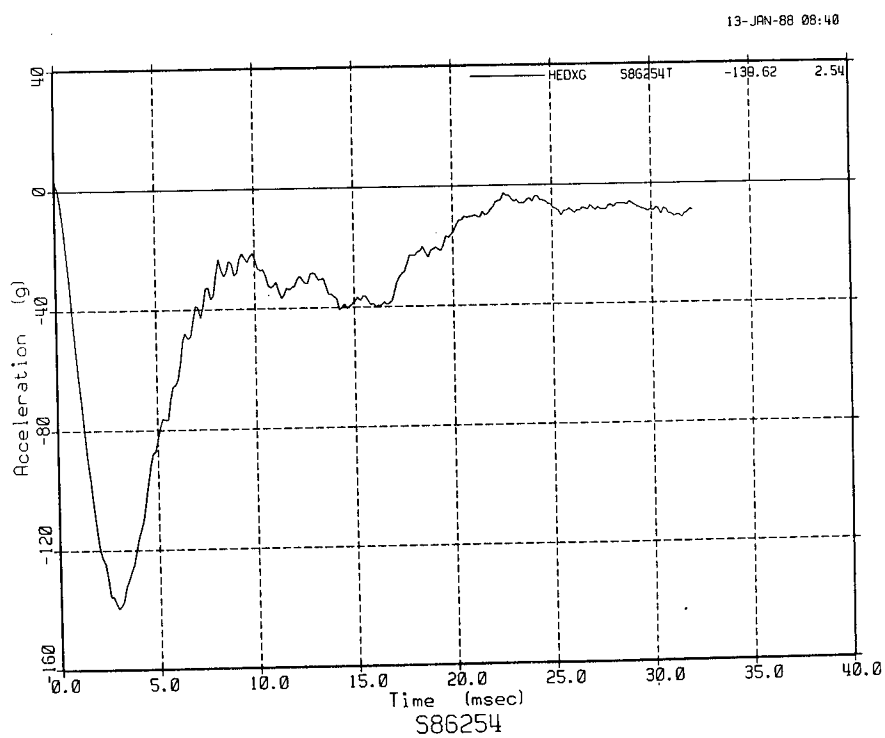
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Time (msec)
S86252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HEDXG S86254T -139.62 2.54
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-40
-80
-120
-160
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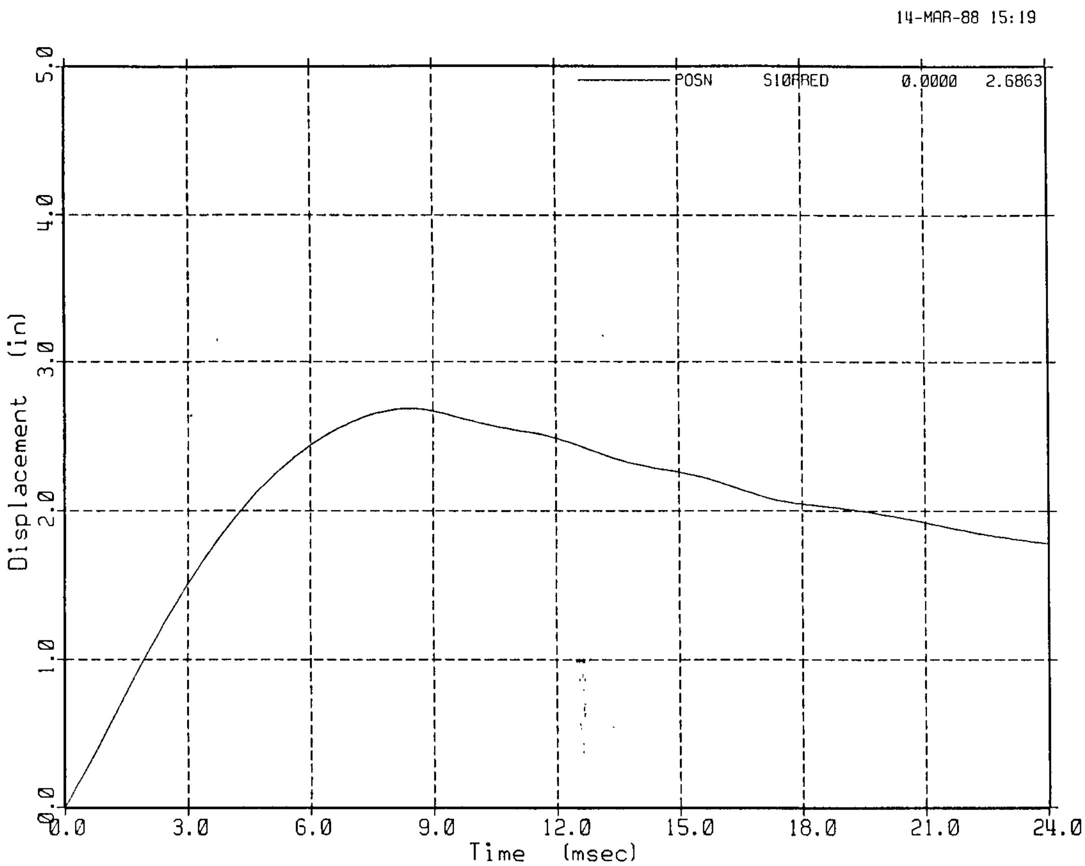
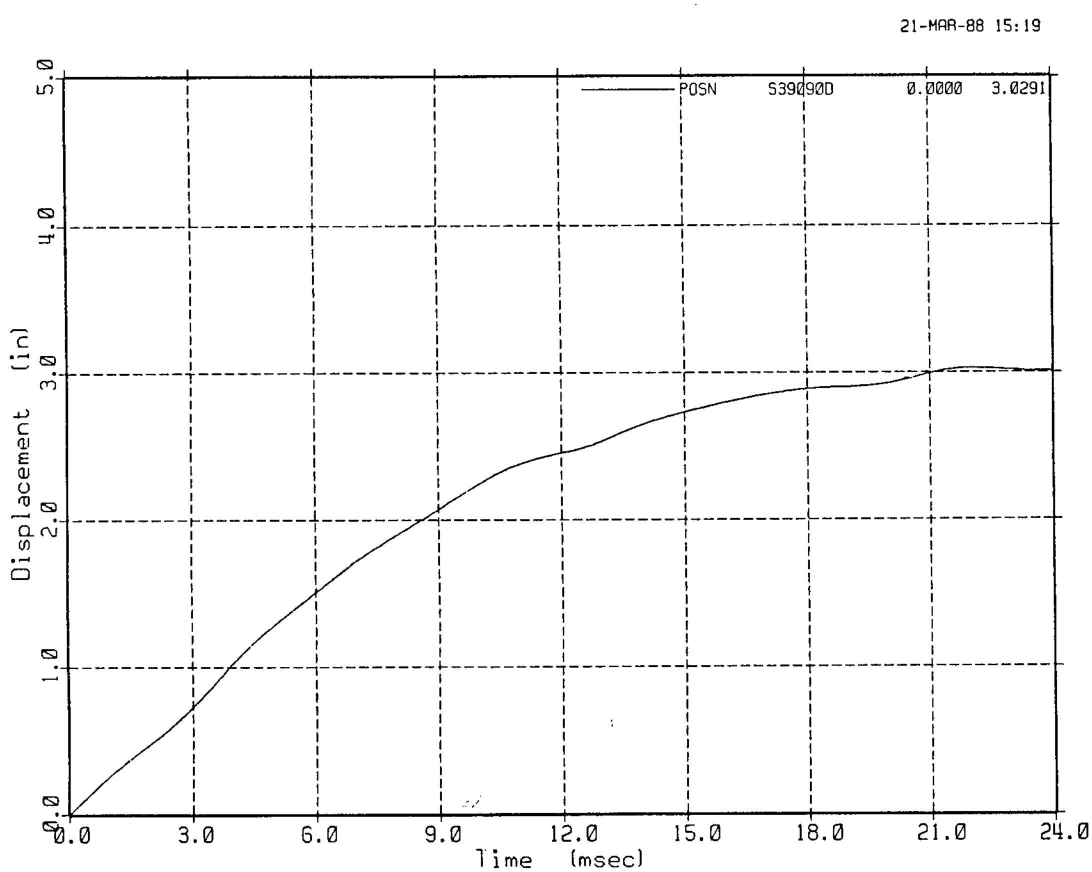
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Time (msec)
S86254



TEST S10RRE



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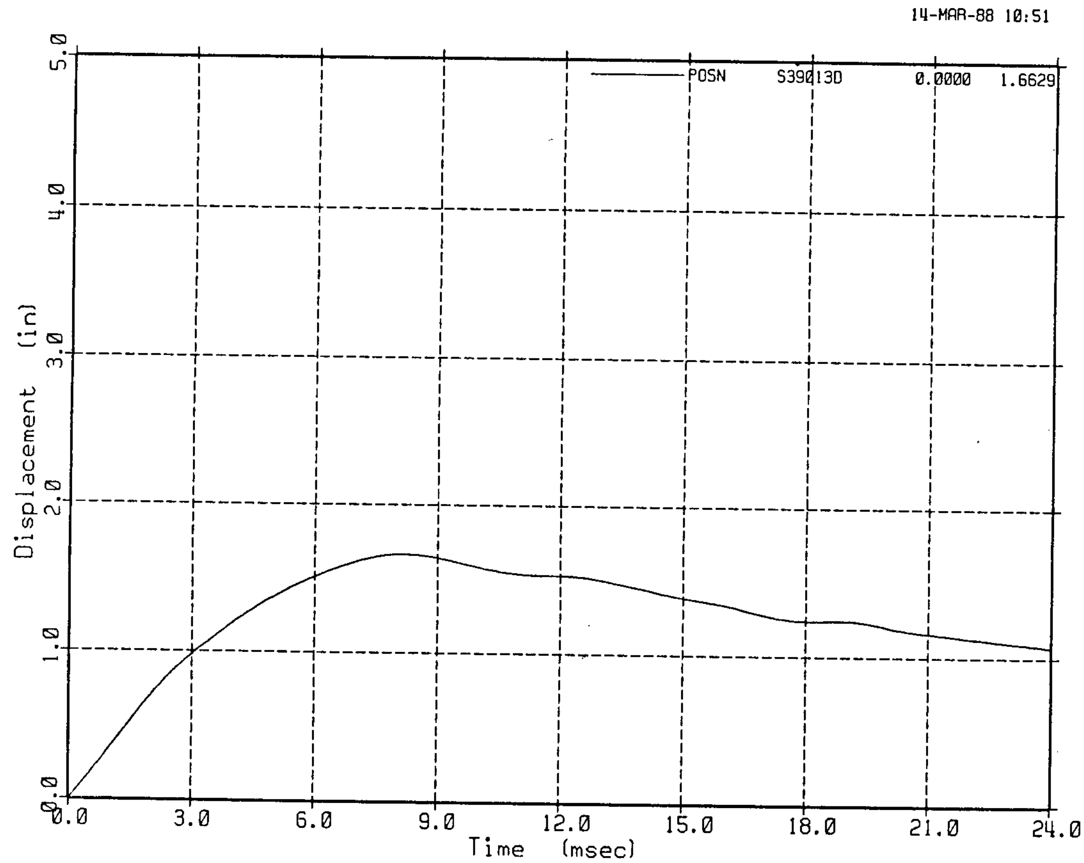

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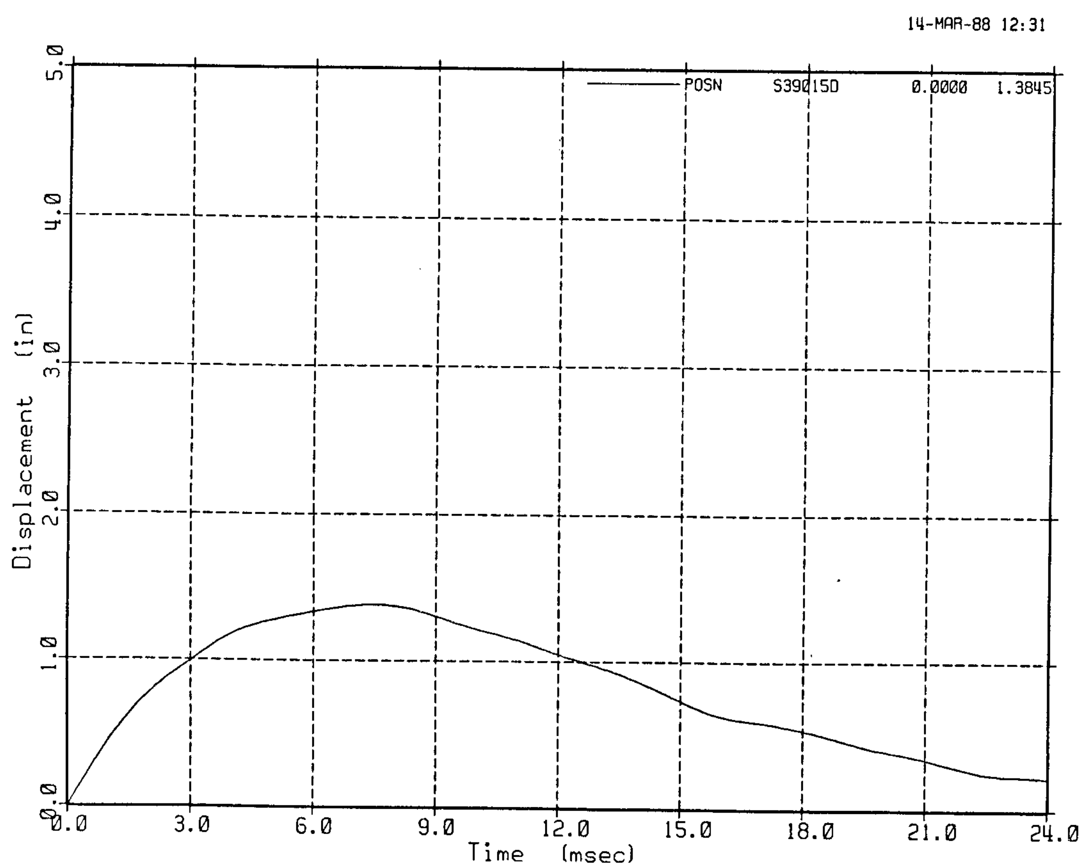

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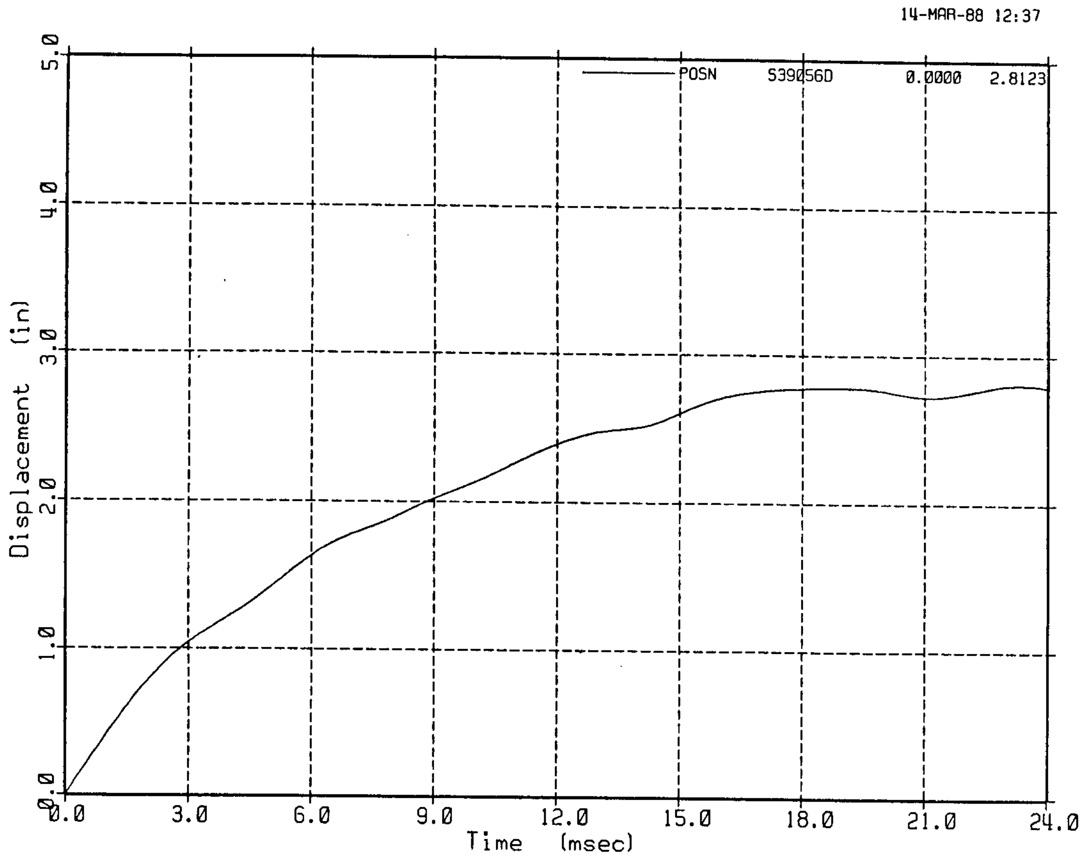

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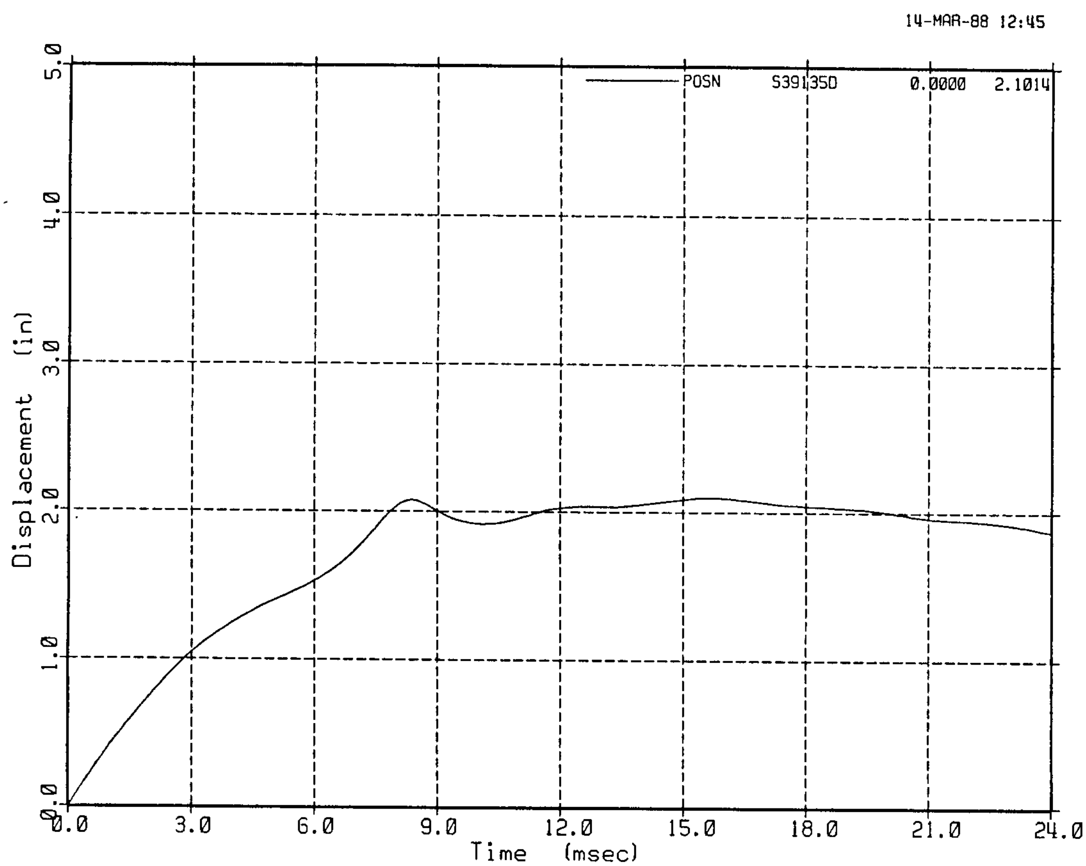

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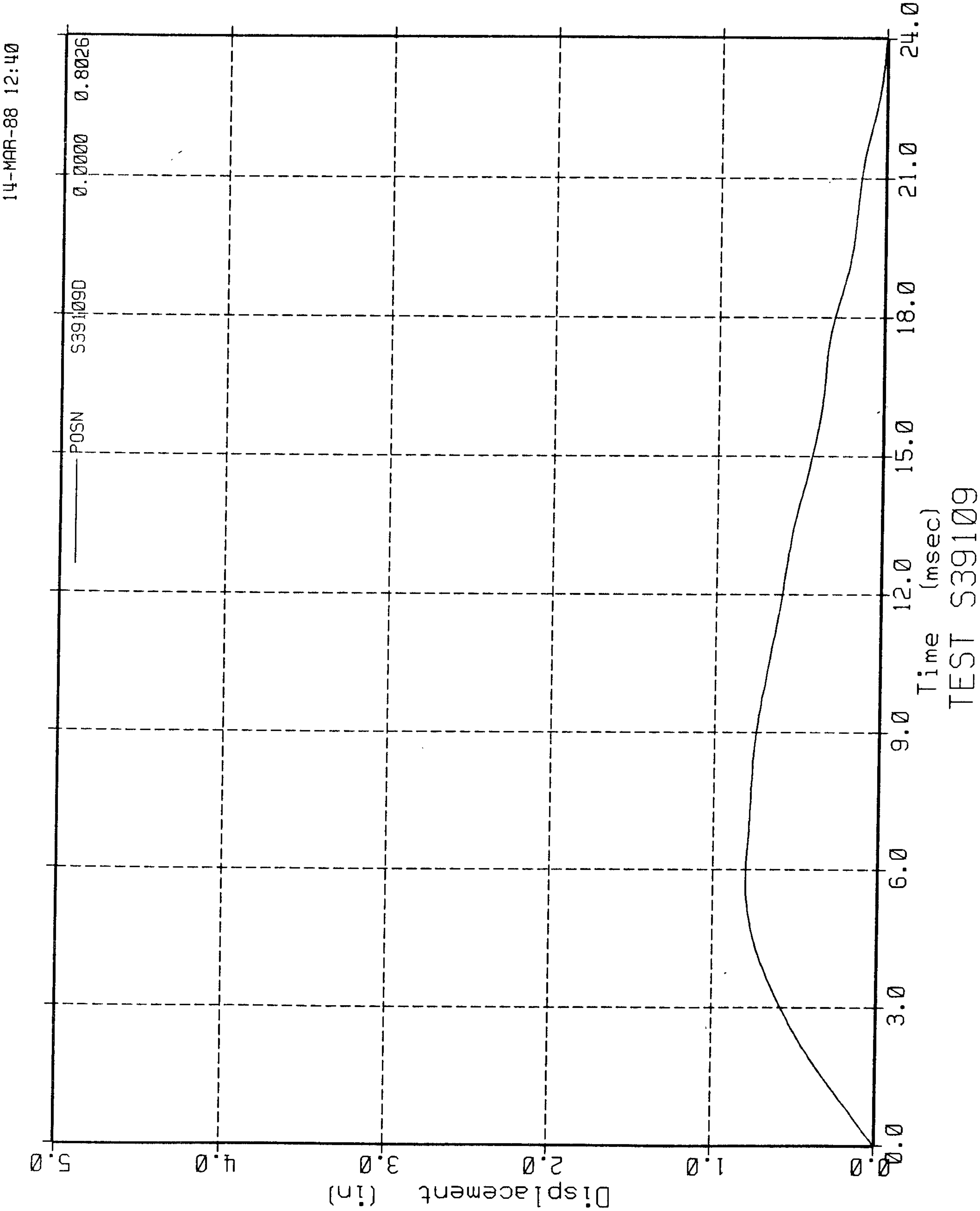

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12.0
15.0
18.0
21.0
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Time (msec)
TEST S39109
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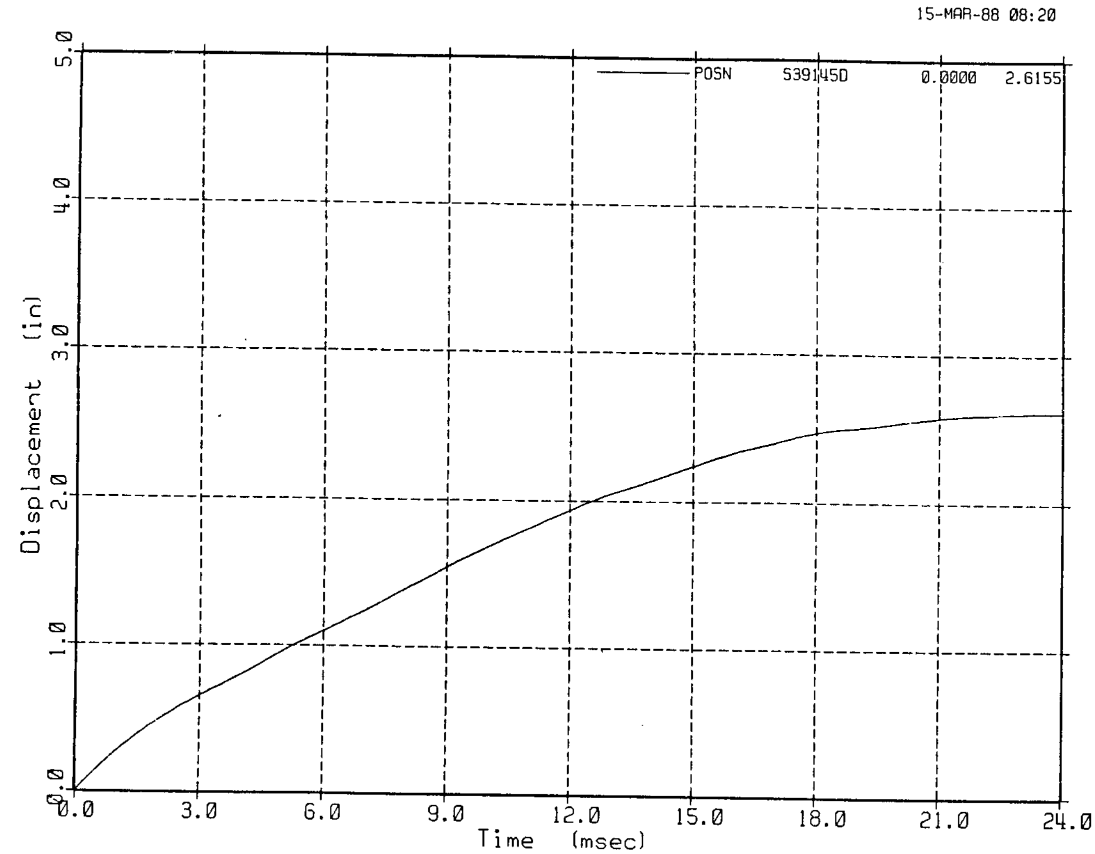
3.0
4.0
5.0
Displacement (in)



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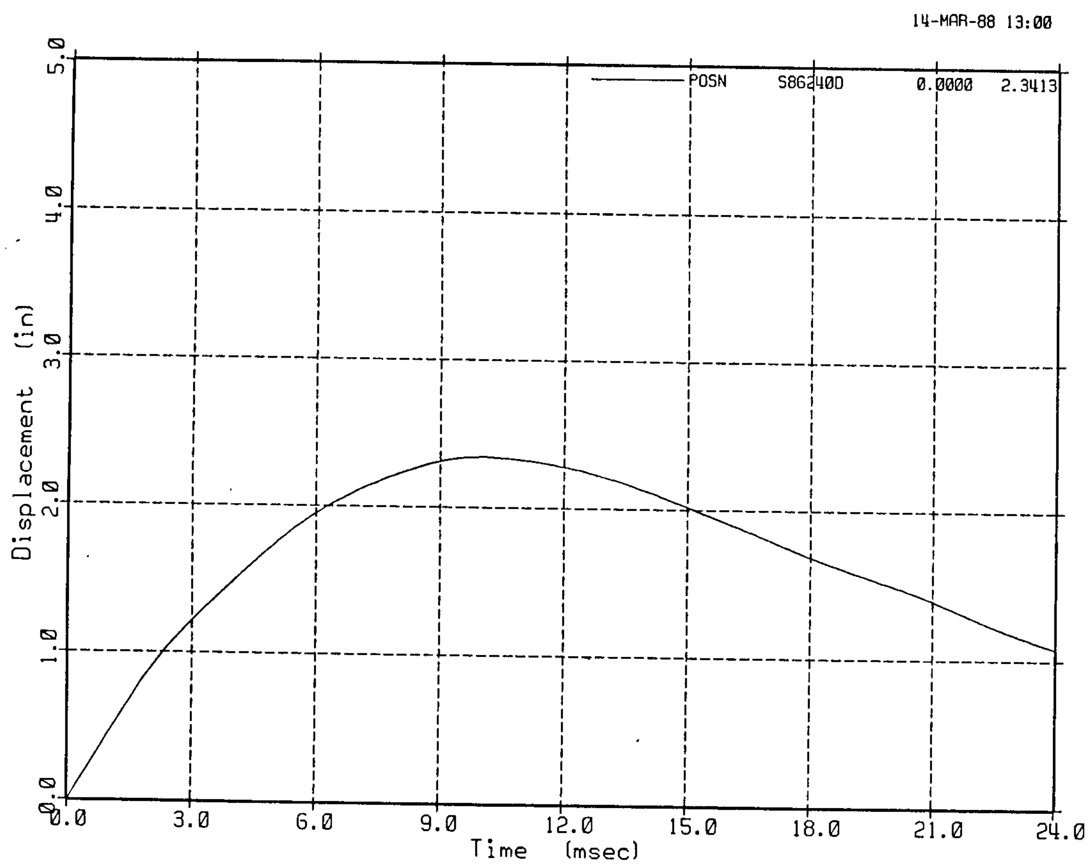

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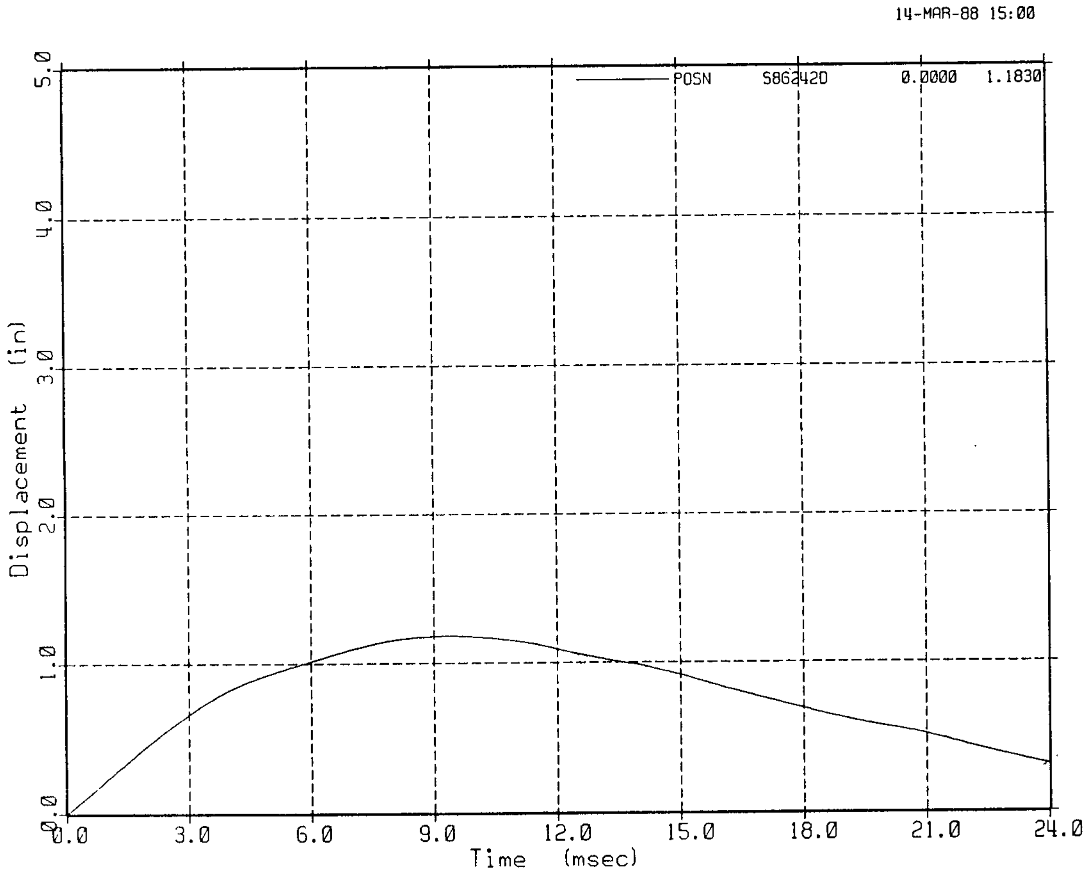

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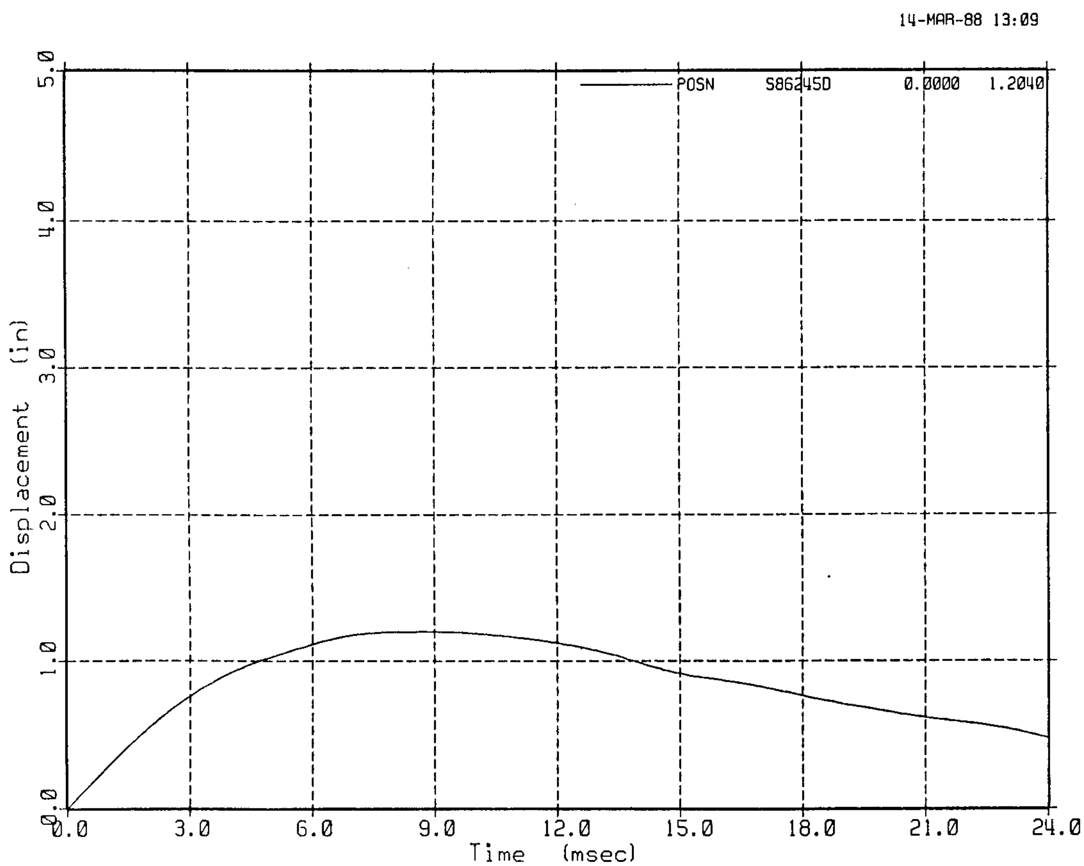

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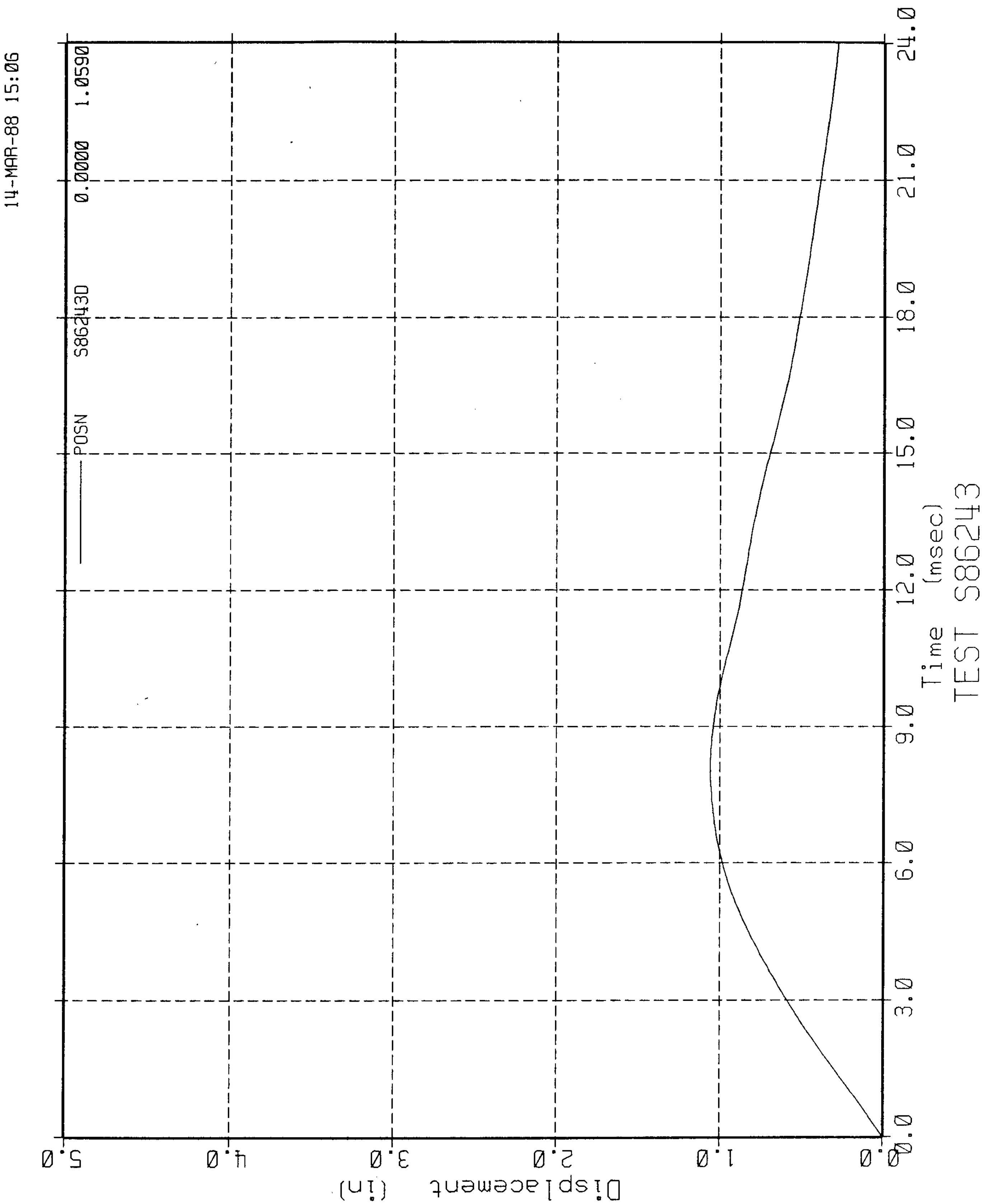
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Time (msec)
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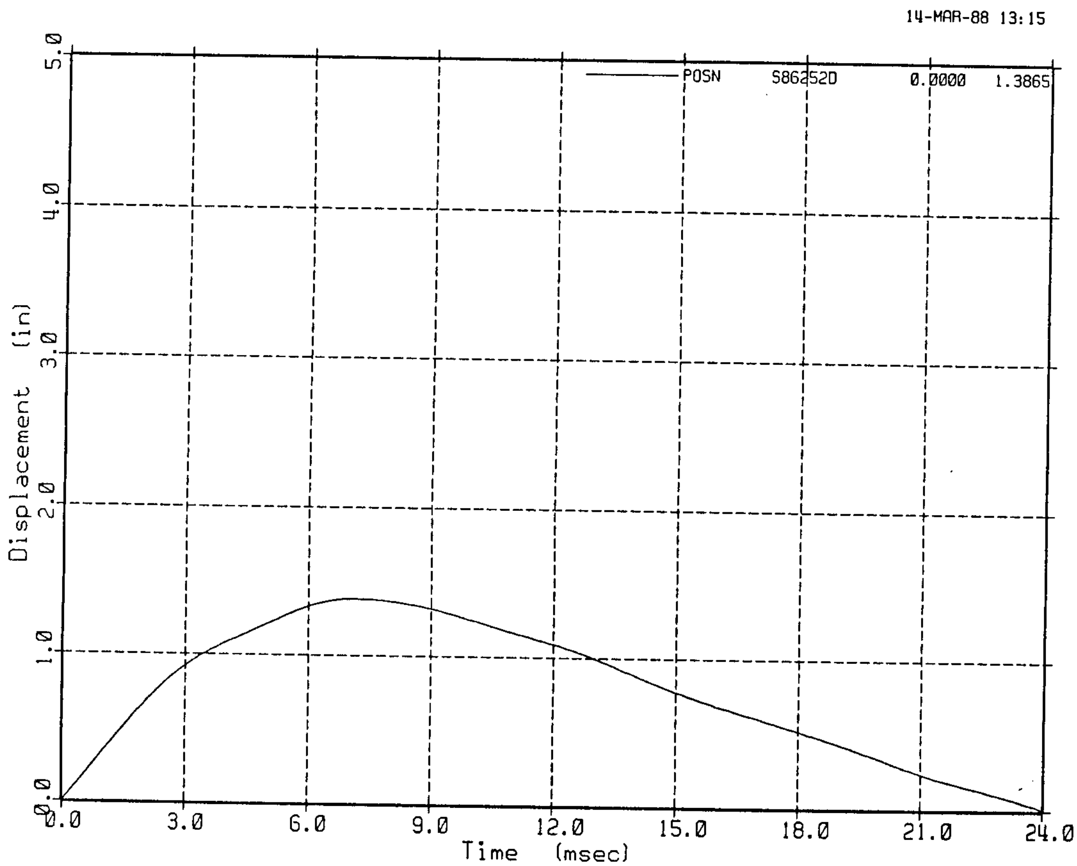
Displacement (in)



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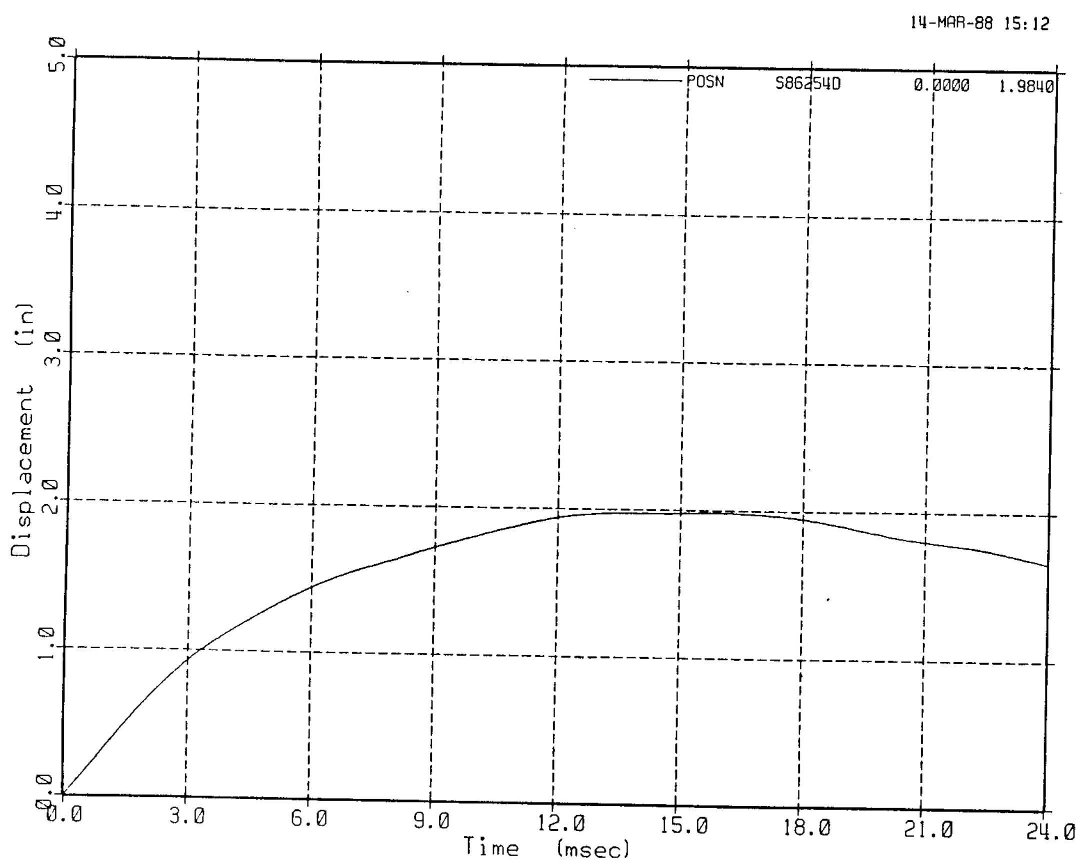

TEST S86254

APPENDIX B

Overall AIS based on the single most severe head injury, is plotted as a function of TMSC and HIC, respectively, in Figures 8 and 12. To avoid the problem of associating discrete AIS values with continuous variables, it is sometimes useful to express results in terms of the probability of inflicting injuries of given severity levels. In this appendix, injury probabilities associated with TMSC and HIC values are estimated.

The data contained in Figure 8 have been divided into three ranges of TMSC values: 0 to 3.0, 3.0 to 6.0, and greater than 6.0. The average TMSC was calculated for each range. Within each range, the probabilities of AIS > 1, 2, 3, 4, and 5 were estimated. For example, in the first range, where 0 < TMSC < 3.0 and average TMSC = 1.88, there are six data points -- two AIS 1's and four AIS 2's. Therefore, for TMSC = 1.88, the probability of an AIS > 1 is estimated to be 4/6 = 0.67, and the probability of an AIS > 2 is estimated to be 0. Estimates were made similarly in the other data ranges. The results are presented in Figure B-1.

In the same manner, injury severity probability values as functions of HIC were estimated. The three HIC ranges were chosen to be 0 to 1000, 1000 to 2000, and greater than 2000. Results of this analysis are shown in Figure B-2.

TMSC		PROBABILITY OF:				
Range	Average	AIS > 1	AIS > 2	AIS > 3	AIS > 4	AIS > 5
0-3	1.88	.67	0	0	0	0
3-6	4.62	.75	.75	.50	.25	0
> 6	7.50	1.00	1.00	1.00	.50	.25

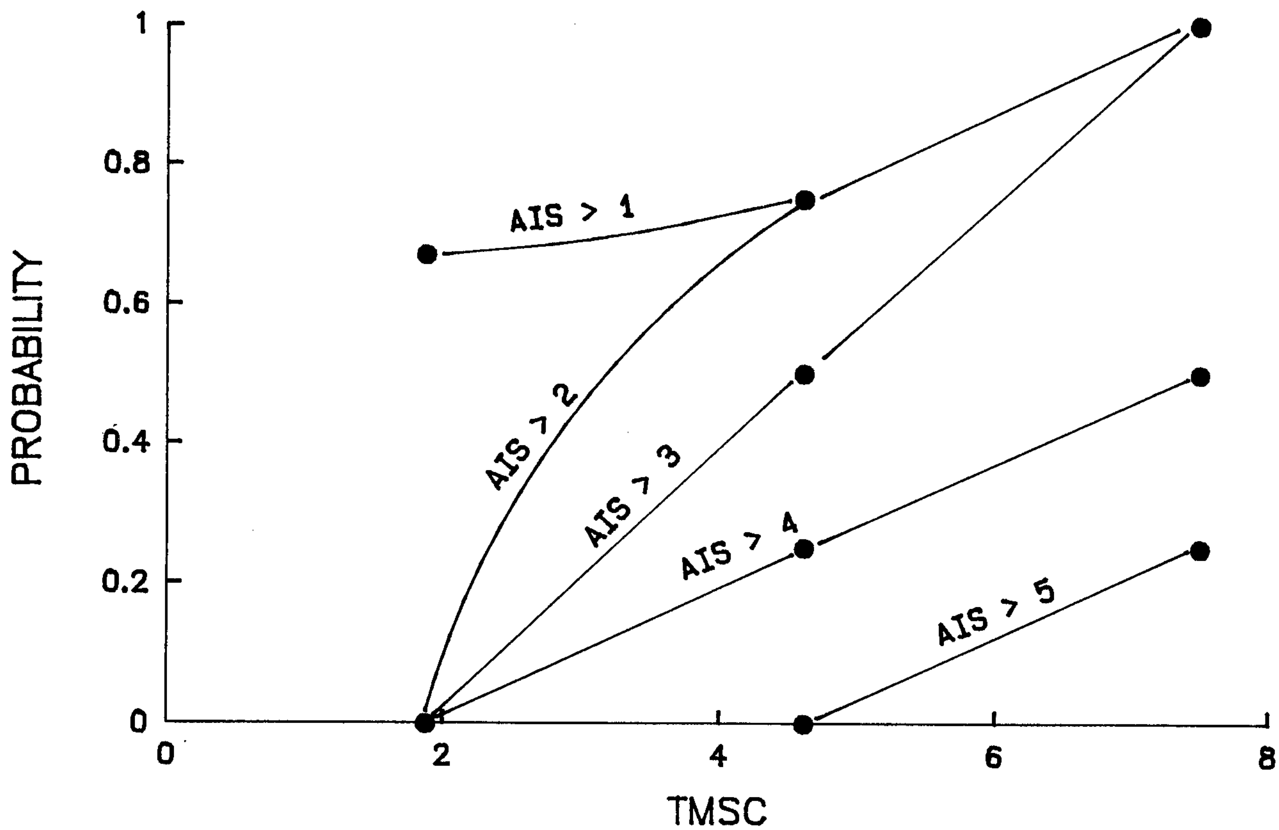

FIGURE B-1 -- Injury Probability Estimates -- TMSC

HIC		PROBABILITY OF:				
Range	Average	AIS > 1	AIS > 2	AIS > 3	AIS > 4	AIS > 5
0 - 1000	526	.57	.14	0	0	0
1000 - 2000	1369	1.00	.80	.80	.20	0
> 2000	2937	1.00	1.00	1.00	1.00	.50

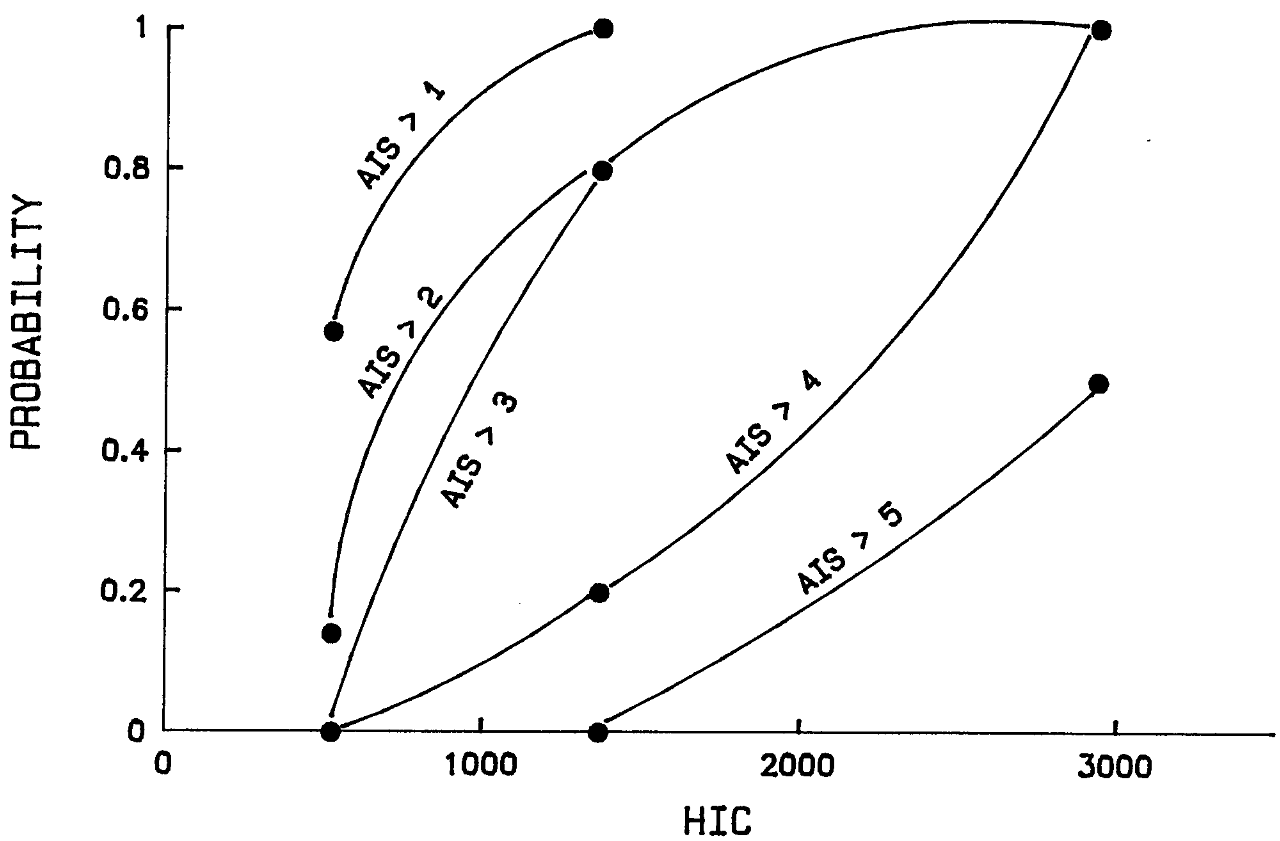

FIGURE B-2 -- Injury Probability Estimates -- HIC